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ELECTRICAL PHENOMENA IN THE POSITIVE COLUMN AT LOW PRESSURE

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After a brief discussion of the ignition of a self-supporting discharge and of the transition from glow to arc discharge the stationary state of the positive column is treated in detail. In addition a discussion is given of the transport of charge by electrons and ions with the accompanying production of light and ionization to replace the loss of charged particles due to the current to the wall. The current density is not uniform over the cross section, but is a maximum at the axis. The influence of this current distribution on excitation and ionization is examined for sodium and mercury low pressure discharges.

Introduction

An electric current in a conductor consists of the transport of particles, electrons and ions, which carry one or more elementary charges [1]). In the case of metals one or more electrons are freed from the atoms and can move freely in the metal (conduction electrons). The remaining positive ions are bound to a given spot, apart from possible oscillations around their equilibrium positions, and form the lattice. If a potential difference is applied to the ends of a wire, the numerous conduction electrons (the number per cm³, n_e, is 6×10^{22} for silver), because of their negative charge, move in the direction of the positive pole, the anode. In the stationary state just as many electrons enter the wire per second at the negative pole, the cathode, as leave it at the anode. Since the positive ions of the lattice are bound to their places they do not contribute to the current.

In the case of an electrolyte both positive and negative particles are mobile. Under the influence of an electric field the positive ions move toward the cathode and the negative particles, which in this case are not free electrons but negative ions, move toward the anode. Also in this case the charged particles are already present under ordinary conditions when no electric field is applied; the field serves only to set the charges in motion in a definite direction.

An insulator or non-conductor contains no freely moving charges in the normal state. If such charges are introduced in some way or other the non-conductor becomes a conductor: for example an evacuated space into which electrons are introduced by means of a hot cathode (radio valve). The same method could be used in a gas which is an insulator under normal conditions. There is, however, another method of making a gas conducting. In this method the charges in the gas are produced by ionization under the influence of the electric field applied. This is the phenomenon of breakdown which we shall discuss briefly.

Ignition of a self-supporting discharge

If to the terminals of an incandescent lamp a voltage is applied which is equal to one half of the normal working voltage, a current flows whose strength is of the order of magnitude of two thirds of the normal working current. The charges which produce the current were of course already present in the filament, their velocity of movement, however, is less than with the normal working voltage so that the number of charges which pass through every cross section of the filament per sec, *i.e.* the electric current, is smaller.

If in the same way half the working voltage is applied to a gas discharge lamp, apparently nothing happens, *i.e.* with an ordinary ammeter no appreciable current is measured. As a matter of fact, however, a very small current does flow, as may be shown with a galvanometer. As a result of penetrating radiation (radioactive and cosmic) a few ions per cm^3 are always being formed. The radiations referred to are able to free an electron from an atom and thus produce a positive ion at the same time. In the atmosphere such an electron is quickly captured by the oxygen, which can easily bind negative electrons to give a negative ion which sooner or later joins with a positive ion (recombination), and the free charges disappear. In a pure rare gas, however, in which no negative ions occur, the electrons remain free for a much longer time. If such a natural ionization occurs in a rare gas between two plates at different potentials, the electrons will move toward the anode and the positive ions toward the cathode, in other words a current flows through the gas. *Fig. 1* shows the variation of the current between the plates with increasing potential difference. In making these measurements the ionization was produced by irradiation with X-rays, whereby larger currents can be obtained than in ionization by cosmic or radioactive radiation.

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[1]) The elementary charge, which is equal to the charge on an electron is 4.80×10^{-10} e.s.u. $= 1.60 \times 10^{-19}$ coulomb. A single charged positive ion is an atom which has lost one electron, a doubly charged positive ion has lost two. A single charged negative ion is an atom with one extra electron, etc.

The curve of fig. 1 consists of three parts. At very small voltages, V, the current rises and at about 20 volts reaches a saturation value: all the charges formed in the gas arrive at the electrodes, and there is therefore no recombination in the gas or at the wall. If the voltage is further increased the current at first remains constant, but at about 400 volts it begins to increase slowly and then more rapidly. This increase in current is due to the fact that the ions moving under the influence of the electric field themselves cause further ionization of the gas.

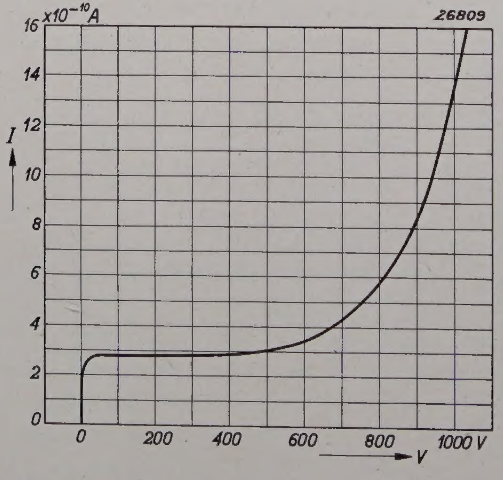

Fig. 1. Variation of the current as a function of the voltage between two large parallel plates (diameter 80 mm, separation 24 mm) with auxiliary ionization in the gas by X-rays. (Argon at a pressure of 27.6 mm).

The energy of the electrons moving toward the anode in the electric field increases. As long as their kinetic energy is less than the excitation energy of the rare gas atoms, they can only give off a very small fraction of their energy of the order of 0.01 per cent in collisions with the latter atoms. Between successive collisions, therefore, the electrons obtain more and more energy, until they are able to excite the atoms or ionize them. An electron which is freed in the neighbourhood of the cathode will then produce a number of electrons on its way to the anode, each of which in turn, after acceleration by the field, can also ionize atoms (*fig. 2*). This phenomenon has been given the appropriate name of electron "avalanche". It occurs more readily the higher the field strength.

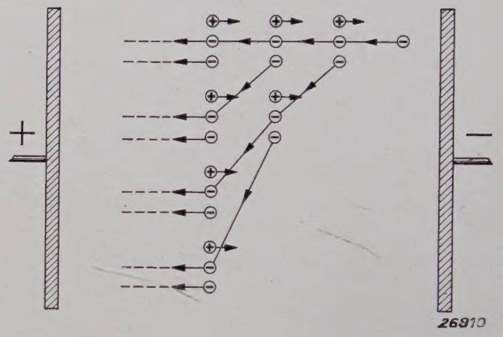

Fig. 2. Diagrammatic representation of an electron avalanche.

If the irradiation with X-rays is interrupted, the current may become very small again: in such a case we are concerned with a "non-selfsupporting discharge" which cannot exist without auxiliary ionization. If, however, the applied voltage is high enough, the interruption of the auxiliary ionization no longer has any effect and we are concerned with a "self-supporting" discharge. The fact that such a discharge may continue is due to the action of the positive ions which free electrons upon striking the cathode, on an average of about one electron per 20 ions. If the field strength and consequently the ionization is so great that for every electron which leaves the cathode 20 ions arrive on it, then one electron can again be freed. This electron in turn provides for 20 ions on the cathode, in other words the process is continuous and we have a "self-supporting discharge". It is clear that this phenomenon will occur at lower field strengths (smaller number of ionizations) the more easily the electrons are freed from the cathode. A tube whose cathode is covered with a barium-barium oxide layer, which gives off electrons readily, will therefore ignite more easily than one with an iron cathode.

Transition from glow to arc discharge

If, as is assumed in the above example, we are concerned with cold cathodes, the series resistance may be so chosen that the self-supporting discharge occurs in the form of a so-called "normal glow discharge". This discharge is distinguished by the fact that it does not cover the whole cathode, and that a voltage jump (100 - 200 volts) occurs at this electrode, the so-called "normal-cathode drop". *Fig. 3* shows schematically a characteristic, *i.e.* the voltage at the terminals of the tube V_l as a function of the current I_l in which the path of the discharge is taken so short that the voltage drop in the cathode region is practically equal to V_l.

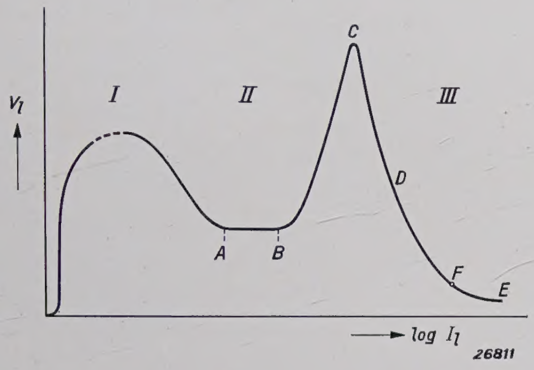

Fig. 3. Diagrammatic representation of the voltage-current characteristic for the discharge between flat plates. The three regions correspond *I* to breakdown, *II* to normal glow discharge and *III* to arc discharge.

In the region of the normal glow discharge *AB* in fig. 3, the current density on the covered part of the cathode is constant for a given cathode material and gas filling. If the current I_l increases, the part of the cathode covered by the glow becomes larger, while the cathode drop V_k remains constant. This continues until the cathode is completely covered (point *B*). If it is desired to increase I_l still further, then the cathode drop increases together with the energy density; one is then concerned with a so-called "abnormal cathode drop".

Nowadays only few gas discharge lamps have a cold cathode (practically only the neon advertising tubes and glow lamps). Most discharge lamps have a hot cathode which is raised to and maintained at the proper temperature by the discharge. Upon ignition a glow discharge first occurs which must of itself pass over into an arc discharge. Such an "arc discharge" is distinguished by a low cathode drop, 10 - 20 volts, which is easily obtained with the help of a hot cathode whose surface is covered with a layer which readily emits electrons (barium-barium oxide).

Finally, on the basis of the diagram in fig. 3, we shall discuss briefly the transition from glow to arc discharge. If the series resistance is so chosen that the discharge is not stabilized in the range of the normal glow discharge *AB*, the current will continue to increase, and when the cathode drop becomes abnormal the voltage V_k will also increase. The consumption of energy in the cathode region, $I_l V_k$, a large part of which is given off to the cathode, may become so great that the latter begins to glow and emit thermions (*c* in fig. 3). The number of ions necessary to free electrons from the cathode then becomes considerably smaller, and the cathode drop falls to 10 - 20 volts (part *DE* of the characteristic in fig. 3). By appropriate choice of the series apparatus the discharge can again be stabilized at any arbitrary point of the characteristic, for instance at *F*.

This transition from glow to arc discharge is, like the original ignition, facilitated by using electrodes covered with a layer having a high electron emission. The temperature at which a given electron emission is reached, is then lower. Moreover, the electrodes are made so small, that they may be raised to the necessary temperature rapidly with a relatively small amount of power and maintained at that temperature.

Stationary state of the positive column. Part played by ionization

In the discharge whose characteristic is given in fig. 3 the length of path of the discharge was assumed to be short, so that only those phenomena taking place in the neighbourhood of the cathode played an important part. When, however, a much longer path of the discharge is taken, as for example, in a neon tube for advertising purposes, the phenomena at the electrodes become relatively less important. The long portion of the discharge joining the region near the cathode with that near the anode, the so-called positive column, then determines the character of the discharge.

In the first place one may ask how the conduction takes place in this part of the discharge. For the sake of simplicity we assume that the discharge takes place in a rare gas at low pressure (<5 cm Hg) and with direct current. A large number of electrons come from the cathode region and move in the direction of the anode under the influence of the electric field. If there were only electrons in the gas they would give rise to a considerable space charge and a steep drop in potential. Several hundred volts per centimeter would then be necessary to cause any appreciable current to pass through the positive column, whilst actually the field strength is usually several volts per centimeter. The negative space charge of the electrons is, however, neutralized by the positive ions present. The number of electrons in every cubic centimeter, the concentration n_e, is practically equal to the number of positive ions n_p 2); the space charge in the column is practically zero. The values of the concentrations n_e and n_p found in such a low pressure column are approximately $n_e = n_p = 10^{10}$ per cm³. At a pressure of for instance of 10 mm and a temperature of 300° C, the concentration of the neutral atoms $n = 1.7 \times 10^{17}$ per cm³, so that one in ten million is ionized.

Although the concentrations of the electrons and of the ions are practically equal, the current may be almost entirely ascribed to the transport of charges by the electrons. This is the result of the much greater mobility of the electrons compared with that of the ions under otherwise similar conditions of field strength and gas pressure. The mobility, *i.e.* the velocity of displacement in the field direction at unit field strength is proportional to the mean free path (the average distance between two successive collisions) and inversely proportional to the mass. In the case of the electron the mean free path is longer and the mass is considerably smaller than that of a positive ion. Thus for example the mobility of the electrons K_e in neon at a pressure of 1 mm and at 0°C at 1 volt/cm equals 1.4×10^6 cm/sec, and for the ions $K_p = 7.5 \times 10^3$ cm/sec. The current density in the tube is proportional to the concentration and the mobility, according to the formula $j_e = n_e K_e \cdot E$ (E = field strength). If the current density of the electrons is compared with that of the ions, since $K_e \gg K_p$, $j_e \gg j_p$ also. In spite of the fact the ions contribute almost nothing to the electric current, they are nevertheless indispensable because they neutralize the negative space charge of the electrons.

Conduction in an ionized gas is therefore somewhat analogous to that in a metal in which electrons also move about among positive ions. There is, however, an important difference, since in a metal the ions of the lattice are bound to their places while in the positive column they can move. In the positive column they move toward the wall and are there lost by recombination with electrons of the negative wall charge, so that neutral atoms are again formed. The ions and electrons which disappear on the wall by recombination must be replaced by others, and this replacement is made by the electrons in the bulk of the gas. The energy necessary for this is taken from the electric field, which at the same time provides for their displacement in the direction of the anode.

Energy distribution of the electrons. Light emission.

As is well known, an electron, if it is to produce an ion in a collision with a neutral, non-excited atom, must have a kinetic energy at least equal to the ionization energy of that atom. The energy of an electron $\frac{1}{2} m_e v_e^2$ is usually given by indicating the potential difference (in volts) which it must pass through in order to obtain the given energy $\frac{1}{2} m_e v_e^2 = e V_e$. For a 5-volt electron therefore, the energy $e V_e = 4.8 \times 10^{-10}$ (e.s.u.) $\times$ 5/300 (e.s.u.) $= 8 \times 10^{-12}$ erg $= 8 \times 10^{-19}$ watt sec, whilst $v_e = 1.33 \times 10^8$ cm/sec. Not all electrons have sufficient energy for the ionization of a neutral atom; there is a Maxwellian distribution of velocities in the positive column. *Fig. 4* shows this graphically. In the figure the fraction of the electrons which have a velocity between v and $v + dv$ (cross-hatched area) is plotted as a function of v. It may be seen that there are only a few electrons which have either a very high or a very low velocity, most of them have a velocity in the neighbourhood of the commonest value v_w at the maximum of the curve. In fig. 4 are further indicated the average and quadratic velocities, $\bar{v}$, and $\sqrt{\overline{v^2}} = v_f$ respectively. Also are indicated the velocities v_a and v_i of an electron having an energy equal to the excitation ($e V_a = \frac{1}{2} m_e v_a^2$) and ionization ($e V_i = \frac{1}{2} m_e v_i^2$) energies respectively of the gas atoms. An excitation

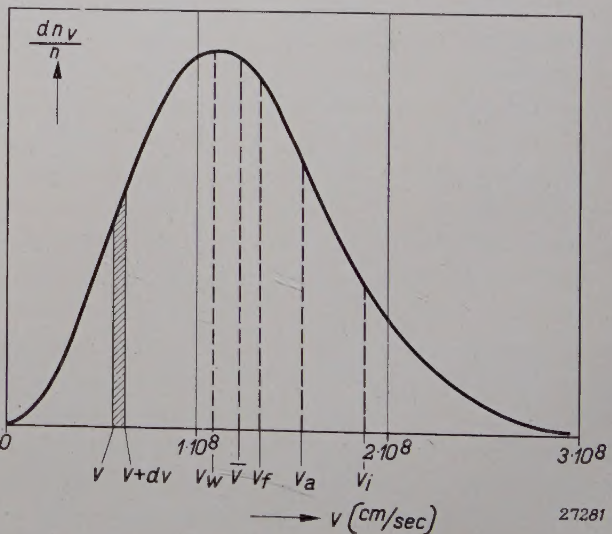

Fig. 4. Maxwellian distribution of the velocities of the electrons. The ordinates give the fraction dn_v/n of the electrons with a velocity between v and $v + dv$. v_w, velocity most commonly occurring, $\bar{v}$, average velocity, and v_f, quadratic average velocity. (The average energy in this example corresponds to a voltage of 5 volts, $\frac{1}{2} m_e v_f^2 = e \overline{V}_e$, where $\overline{V}_e$ = 5 volts).

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2) We are supposing that the discharge takes place in a rare gas in which we assume that no negative ions occur.

potential $V_a = 7$ volts and an ionization potential $V_i = 10$ volts is hereby assumed, while the average energy of the electrons is set at $\overline{V}_e = 5$ volts ($^1/_2\, m_e \overline{v_e^2} = e\overline{V}_e$). If in the positive column there are electrons which have sufficient energy for ionization, excitation will also occur since the excitation voltage V_a is less than the ionization voltage V_i. The light emission, a result of the excitation of atoms, although it is important in the problem of illumination, is therefore only a by-product of the discharge mechanism. If care is taken that the loss of ions from the path of the discharge is kept small by a large diameter and a suitably chosen gas pressure, a "dark" column, *i.e.* a column through which a high current flows but which gives almost no light can be obtained. Since in this case practically no ionization occurs to replace the ions which have disappeared, the average speed of the electrons remains low, and the excitation of the gas slight. Such discharges have a low field strength, since the field only serves for the displacement of the electrons, in which process only very small energy losses occur due to elastic collisions of the electrons with atoms.

Mechanism of the column discharge. Current to the wall

The following picture of the positive column may serve to summarize the foregoing discussion. A cloud of electrons whose velocities are given by a Maxwellian distribution is displaced in the direction of the anode under the influence of the electric field. The velocities of the individual electrons may have any arbitrary direction, since after covering a free path where the velocity increases in the direction of the field, a collision with an atom takes place so that the velocity continually changes its direction. Due to the action of the electric field, however, there is a resultant velocity in the direction of the anode.

While the cloud is being displaced the electrons gain an amount of energy which, in the stationary state, is just equal to the loss of energy due to elastic collisions, excitation and ionization. Over the whole length of the column the average energy remains constant.

Compared to the electrons the ions may be considered as almost stationary. They do, however, describe curved paths, the form of which is due to the fact that on the way to the wall they are also displaced somewhat in the direction of the cathode. We shall now consider in more detail the lateral movement of the ions which causes the loss of positive charges.

If a foreign gas, for instance chlorine which is easily recognizable by its odour, is introduced at a given place into a body of another gas, for instance the air of a room, it will be found that after a short time the chlorine will have spread throughout the whole mass. This is the result of diffusion which tends to abolish differences of concentration. Diffusion proceeds more rapidly the greater the free path and the velocity of the particles introduced. If an equal number of electrons and ions are introduced locally into a rare gas atmosphere, the electrons will diffuse away more quickly. The ions remaining behind will, however, due to the electrical attraction, have a retarding action on the diffusion of the electrons, and conversely the rapidly moving electrons will accelerate the diffusion of the ions.

A similar phenomenon takes place in the positive column: the electrons diffuse more rapidly away from the middle of the path of the discharge and carry the slower ions with them. They then encounter the wall as an obstacle and charge this negatively, so that the wall attracts ions and repels electrons. This negative charging of the wall proceeds until, on an average, the ions are so much accelerated and the electrons so much retarded that per unit of time just as many positive as negative charges arrive at the wall. A stationary state is then reached in which the charges arriving in equal numbers disappear by recombination on the insulating wall. The phenomenon here described bears the name of ambipolar diffusion current.

The variation of the potential along a radius perpendicular to the axis of the tube is given in *fig. 5a*. Starting from the axis the potential decreases

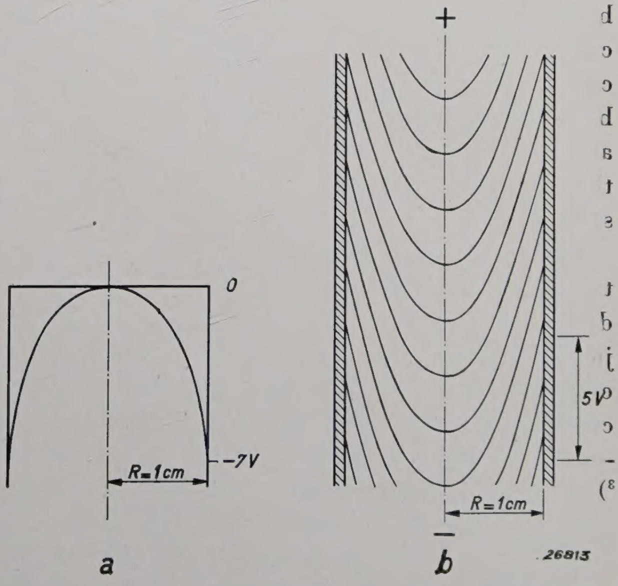

Fig. 5. *a* Potential variation along the radius, *b* Curvature of the equipotential planes.

at first slowly and then more rapidly in the neighbourhood of the wall [3]). The ions are therefore accelerated and the electrons retarded in their movement toward the wall. Only the speediest of the electrons are able to reach the wall, the slower electrons are reflected and return to the axis of the discharge path.

Fig. 5b gives diagrammatically the curvature of the equipotential planes.

For the sake of simplicity it is here assumed that no striae appear in the column as is often the case in the rare gases. The stationary striae are distinguished by the alternately light and dark parts of the discharge. The field strength, the energy and the concentration of the electrons then show periodic fluctuations. Moving striae may also appear which may be observed with the aid of a rotating mirror.

Distribution of current in the discharge cross section

Since the potential decreases from the axis to the wall, the slower electrons will be unable to run counter to the retarding field and the concentration n_e as well as n_p will decrease in the direction of the wall. The variation of the concentration as a function of the distance to the axis can be derived in the following way.

We consider in a piece of the discharge tube 1 cm in length a small volume bounded by two concentric cylinders with radii r and $r + \mathrm{d}r$ which differ only slightly and by two planes perpendicular to the axis (*fig. 6*). In the stationary state just as many charges must enter this volume as leave it, since it is assumed on reasonable grounds that no loss of charge takes place in the gas by recombination. Moreover, the current is the same at all cross sections of the tube so that just as many charges enter at one plane along the axis as leave it by the other. This holds for the electrons as well as for the ions. It is therefore enough to consider the transport of charge through the cylindrical shell.

In the direction perpendicular to the axis this transport of charge takes place by the above-described ambipolar diffusion current, whereby just as many electrons as ions pass through a cylindrical shell per second, since the resultant current must be zero because of the insulating wall. The number of particles which passes through 1 cm² of the surface of the cylinder is proportional to the drop in concentration along the radius

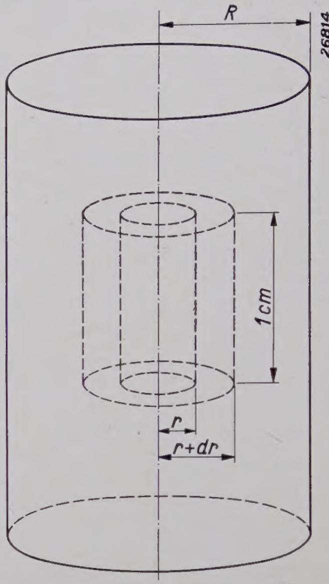

Fig. 6. Volume element between concentric cylinders with radii r and $r + \mathrm{d}r$.

$\mathrm{d}n_e/\mathrm{d}r$, and to the so-called diffusion constant D. The latter depends upon the velocity $\overline{v}$ and the mean free path x; the greater these values, the more rapid the diffusion. For the surface of the inner cylinder therefore we find the number of electrons entering:

$$-D\,2\pi r\cdot 1\cdot\left(\frac{\mathrm{d}n_e}{\mathrm{d}r}\right)_r\ ^{4)}.$$

In the same way for the number of electrons passing out through the outer cylinder we find:

$$-D\,2\pi\,(r+\mathrm{d}r)\cdot\left(\frac{\mathrm{d}n_e}{\mathrm{d}r}\right)_{r+\mathrm{d}r}.$$

The difference between these two expressions gives the number which finally passes out of the volume considered by diffusion in excess of those which entered. This number must be equal to the number formed anew by ionization. The number of ionizations is proportional to the electron concentration n_e and to the number of collisions between electrons and atoms; in addition it increases with the average energy of the electrons. If we let z equal the average number of new electrons formed per electron per second, then the number of ionizations in the cylindrical shell per second is $2\pi r\,\mathrm{d}r\cdot z\cdot n_e$. This must now be equal to the above determined loss by diffusion. From this the differential equation below can be derived, which contains as dependent variable the concentration n_e, as independent variable the distance r to the axis and in addition only known quantities:

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[3]) $n_e = n_p$ holds strictly only at points on the axis; the field is there in the direction of the axis and has no radial components. At other points n_p is somewhat larger than n_e, the difference is, however, so slight that it may usually be neglected. Per centimeter length of tube the sum of negative wall charge and positive space charge is exactly zero.

[4]) In spite of its negative sign, this expression is actually positive, since $\frac{\mathrm{d}n_e}{\mathrm{d}r} < 0$ (n_e decreases with increasing r).

$$\frac{\mathrm{d}^2 n_e}{\mathrm{d}r^2} + \frac{1}{r}\frac{\mathrm{d}\,n_e}{\mathrm{d}r} + \frac{z}{D}\,n_e = 0$$

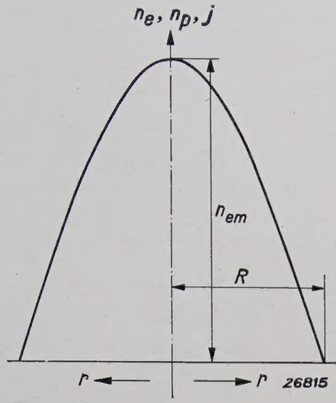


Fig. 7. Variation of the electron concentration n_e, the ion concentration n_p and the current density j as functions of the distance from the axis.

If the new variable, $x = r\sqrt{z/D}$, is introduced into this equation, a differential equation is obtained a solution of which, finite for $x = 0$ (at the axis), is given by the so-called Bessel function of the zero order:

$$n_e = n_{em}\,J_0\,(x).$$

n_{em} is the concentration of electrons at the axis.

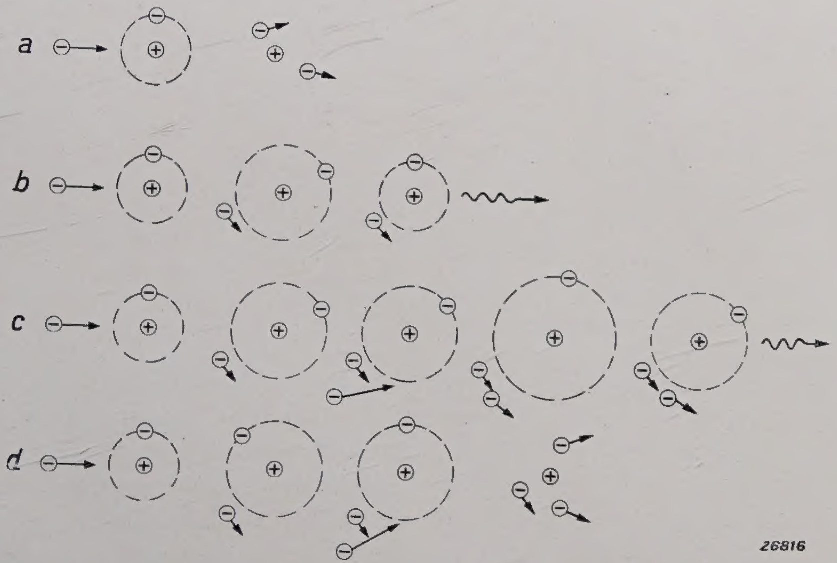


Fig. 8. Schematic representation of excitation and ionization by electron impacts: *a*) ionization upon a single impact, *b*) excitation upon a single impact with consequent emission of light, *c*) cumulative excitation by two successive impacts with light emission, *d*) cumulative ionization by two successive impacts.

The function $J_0\,(x)$ is zero for $x = 2.405$, and since it is assumed that $n_e = 0$ at the wall, for $r = R$, we may write $2.405 = R\sqrt{z/D}$, from which it follows that $\sqrt{z/D} = 2.405/R$. For the concentration n_e as a function of r we find:

$$n_e = n_{em}\,J_0\,(r\,\sqrt{z/D}) = n_{em}\,J_0\left(2.405\,.\,\frac{r}{R}\right).$$

The variation of n_e as a function of r is given in *fig.* 7. Since the field strength in the direction of the axis is the same over the whole diameter, and the current density is proportional to the concentration n_e, the curve of fig. 7 also represents the variation of the current density as a function of the radius.

Influence of the current distribution on ionization and excitation

Although the result of the above derivation is very well confirmed by measurements, it can nevertheless only be correct as a first approximation, since all the so-called cumulative effects are neglected. An example of such an effect is ionization in steps. When an atom is raised to an excited state by collision with an electron it will generally give off the energy taken up in the form of radiation. However, for a very short time it remains in the excited state, usually for about 10^{-8} sec. If the current density j of the discharge is high, and therefore also the electron concentration n_e, the excited atom will have an appreciable chance of undergoing collision with another electron. The result of this second collision may be that the atom is raised to a higher excited state or is ionized (*fig. 8*). The above assumption that the number of ionizations is proportional to the concentration n_e is then no longer entirely correct. It is clear that a current distribution like that given in fig. 7, where the current density is not the same over the whole cross section but has a maximum at the axis, favours the appearance of cumulative effects.

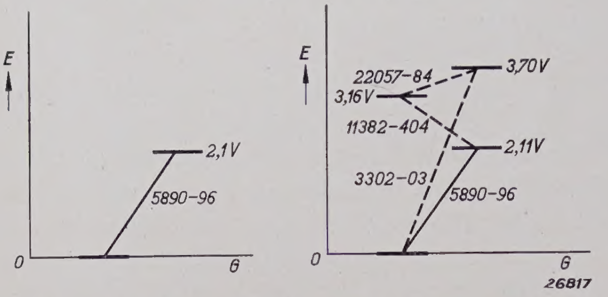


Fig. 9. Simplified diagram of the sodium spectrum. If only the 2.1 volt level is excited only the yellow lines with λ = 5890 and 5896 Å are emitted. When the 3.7 volt level is excited lines outside the visible spectrum are emitted also G = ground, or zero state.

The current distribution found is decidedly favourable to ionization. If ionization takes place in two steps, the energy of the electrons need not be at least V_i volts, but an energy of V_a is sufficient. The diffusion of the electrons to the wall, as well as that of the ions, becomes less so that the loss of ions and the number of ionizations necessary becomes smaller. Apart from this it is already an advantage that the ions are formed mainly in the neighbourhood of the axis. The average distance which the ions must cover before they reach the wall then becomes greater, as well as the time during which they remain in the discharge. We have seen that the part played by the ions consisted in the neutralization of the space charge of the electrons ($n_e = n_p$); if every ion has a longer average life, fewer new ones need be produced per second to keep n_p at the proper value, in other words, the energy required for ionization may be smaller.

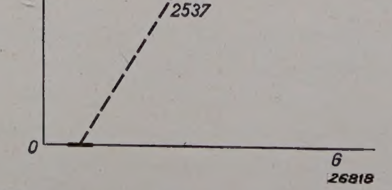


Fig. 10. Simplified scheme of the mercury spectrum. Excitation of the blue line with λ = 4358 Å and of the green line with λ = 5461 Å.

Finally we must not forget that in the case of gas discharge lamps the aim is to attain a maximum emission of light with a minimum consumption of energy. The energy used for ionization must be considered an unavoidable loss.

Whether the current distribution of fig. 7 is favourable or unfavourable to the emission of light depends upon the nature of the states which must be excited. If it is a question of the resonance line (the yellow sodium line for instance) which is emitted when the atom returns to the normal state from the excited state closest to it, concentration of current around the axis is in principle undesirable. Such concentration promotes excitation to higher levels, whereby lines other than the desired resonance line appear (*fig. 9*). In the case of sodium for example, lines in the invisible parts of the spectrum are obtained: infrared and ultraviolet, or lines which are less effective than the yellow line taking into consideration the sensitivity curve of the eye, with as result a decrease of efficiency for illumination.

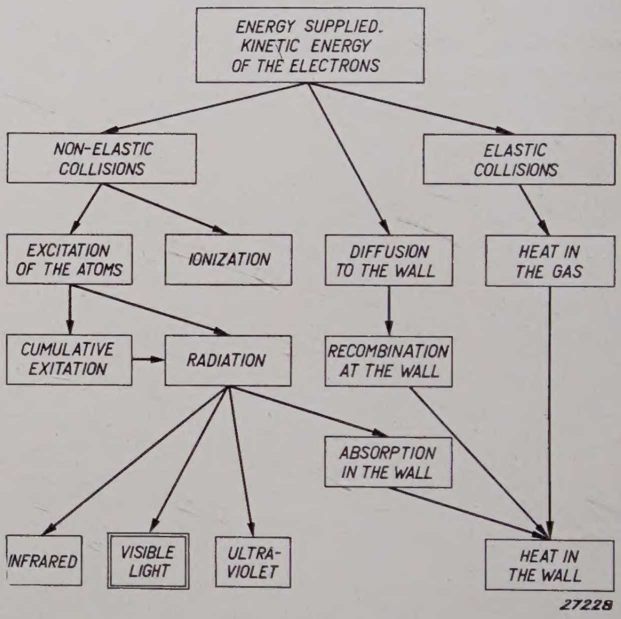


Fig. 11. Survey of the elementary processes in the positive column.

If, on the other hand, it is a question of socalled higher lines which occur upon transitions between two excited levels, the promotion of cumulative effects is desirable. *Fig. 10* makes this clear for the green (5461 Å) and blue (4351 Å) mercury lines. For the production of the blue line, for example, it is more advantageous to bring the atom from the 4.86 volt state, to which it has fallen after emission of the blue line, immediately back again to the 7.69 volt state, than to wait until the atom has returned to the zero state and emitted the ultraviolet line 2537 Å. In the first case only 7.69 - 4.86 = 2.83 volts are needed and this energy is radiated entirely in the visible region; in the second case, however, 7.69 volts are needed of which only 2.83 volts are transformed into visible light.

These cumulative effects are very much favoured in the case of mercury by the fact that 4.86 volts is a "resonance level" and 5.43 volts a so-called "metastable level". Since line 2537 is a resonance line, it is readily absorbed by the atoms in the zero state. After about 10^{-7} sec emission again takes place, and the energy radiated can then be absorbed by another atom in the zero state. This process is repeated very many times before the resonance radiation leaves the tube, so that the concentration of atoms in the 4.86 volt state increases sharply and with it the chance of cumulative excitation from this level to a higher one. For the metastable 5.43 volt level also the chance of cumulative excitation is large. If the atom has been brought into the 5.43 volt level by collision with an electron, it cannot easily return directly to the zero state by emission of radiation, it usually does so by means of collision with other atoms or electrons. The life of such a metastable atom, about 10^{-4} sec., is much longer than that of an atom in an ordinary excited state, so that the chance of cumulative excitation is thereby increased. In the low pressure mercury discharge used in the blue illuminated advertising signs, concentration of the current therefore is an advantage. In the high pressure mercury lamps this phenomenon is even more stimulated by the compression of the discharge to a narrow zone near the axis.

Fig. 11 gives a schematic survey of the various processes here discussed which occur in the positive column.

THERMOJUNCTIONS

by J. W. L. KÖHLER. **621.317.7.082.62**

The construction and action of thermojunctions are discussed in this article. A detailed account is given of the factors which affect the sensitivity and the characteristic of such junctions. The choice of the meter movement and the classification of thermojunctions are explained. Finally a survey is given of Philips thermojunctions.

Introduction

When an alternating current of very low frequency is sent through a suspended coil galvanometer which has its zero point in the middle of the scale, the meter indicates the current at every moment; the pointer moves back and forth with the frequency of the alternating current. If the frequency is raised, then after a moment of resonance the deflection becomes smaller and the pointer finally remains practically still due to the fact that the moving system of the meter cannot follow the high frequency. A suspended coil galvanometer is therefore not suitable for measuring alternating currents. Such currents can only be measured with an instrument whose deflections are always in one direction, no matter what the direction of the current, and whose pointer can therefore adjust itself to a definite average deflection. This condition is fulfilled by dynamometers, soft-iron meters, rectifying meters and thermal instruments. In this article we shall discuss the last type of instruments.

In thermal instruments use is made of the heat development in a resistance, when a current passes through it. It is obvious therefore that the direction of the current can have no influence on the deflection of the meter. The heat developed can be used in various ways:

a) The thermal expansion of the resistance filament can be indicated by a pointer in some way or other.
b) The heat developed can be used to heat a quantity of gas whose increase in volume is indicated by a drop of liquid in a capillary.
c) The change in resistance of a filament forming part of a Wheatstone bridge may be measured.
d) The heating of the filament can be measured with a thermocouple connected to a direct current meter.

We shall treat the last method in detail.

Construction and action of thermo-electric ammeters

Klemenčič was the first to construct a measuring instrument on this principle. The instrument consists of two wires of different materials which form a thermo-electric couple. The two wires are wound together, knotted together or welded together at the middle (see *fig. 1*). The current to be measured is supplied to the terminals *1* and *2*; the wires become warm at the middle due to the heat development; this causes a thermal electromotive force between the terminals *3* and *4*. This voltage can be measured by connecting a sensitive meter to the terminals.

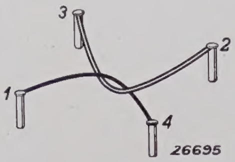


Fig. 1. Klemenčič's thermocouple. The wire of one metal is fastened to terminals *1* and *4*, that of the other metal to terminals *2* and *3*. The wires are joined in the middle electrically in some way. The current to be measured passes through along the terminals *1* and *2*, the galvanometer is connected between *3* and *4*.

There are various objections to this construction which will appear later. *Fig. 2* gives a sketch of a modern thermo-electric ammeter from which it may be seen that the principle is the same as that of the original. A filament is stretched between *1* and *2*. Midway between the terminals a thermocouple is fastened to the filament with its junction on or close to the filament. The ends of the thermocouple are fastened to the terminals *3* and *4*, between which the direct current ammeter is connected. The whole is often placed in an evacuated bulb. When this is done there is no loss of heat by convection, and the sensitivity of the instrument is increased. In certain types the thermocouple is electrically connected with the filament, in others it is insulated from the filament. This construction is not so simple as the original one, but it has certain advantages. One of these is immediately obvious. The thermo-electric properties of the filament material need not be considered, so that the choice becomes much greater.

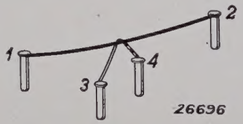


Fig. 2. Modern thermocouple. Between terminals *1* and *2* a filament is stretched, and between *3* and *4* there is a thermocouple whose junction is fastened to the filament.

We shall now discuss the action of the thermo-electric ammeter. If a current i is sent through the filament with the resistance R_g, an amount of heat equal to i^2R_gt will be developed in the filament. The temperature of the filament will thereby be raised; the heat is lost by conduction over the terminals, and by conversion into electrical energy through the thermocouple and by radiation. If the amount of heat which is given up is proportional to the increase in temperature, the latter will be proportional to the heat developed, *i.e.* to i^2. The same is true of the temperature of the junction of the thermocouple. If the thermal electromotive force is proportional to the temperature difference, it will also be proportional to i^2, and the same is true of the current in the circuit comprising thermocouple and galvanometer, which current is proportional to the thermal electromotive force. The deflection of the galvanometer is therefore proportional to the square of the current in the filament.

The ratio between the current through the galvanometer and the current through the filament is called the characteristic of the thermocouple. Here the characteristic is quadratic. Therefore, with a meter having a quadratic scale division, after calibration of one point on the scale, the primary current may be read off directly. A meter with a linear scale can also be used, the reading is then proportional to i^2, *i.e.* to the energy which can be developed by the primary current in a resistance; this method of measurement has many practical applications.

Mathematical analysis

We shall give a brief account of the mathematical analysis of the action of the thermo-ammeter. We shall first consider the filament alone without the thermocouple. The following differential equation holds for the temperature increase in a straight wire stretched between two points and heated by a current:

$$\frac{\mathrm{d}^2\tau}{\mathrm{d}x^2} - \frac{\sigma u}{\lambda q}\tau + \frac{A i^2 \varrho}{\lambda q^2} = 0 \quad \cdot \cdot \cdot \cdot \quad (1)$$

Where:

x	the coordinate of length of the wire from the middle in centimetres,
τ	the temperature difference with respect to the surroundings at the point x in degrees centigrade,
u	the circumference of the wire in centimetres,
q	the area of the cross section of the wire in square centimetres,
i	the electric current in amperes,

- A the electrical equivalent of heat, 0.2388 calories per watt second,
- ϱ the specific resistance of the wire in ohm centimetres,
- σ the heat radiation in calories per centimetre second,
- λ the specific conductivity for heat, in cal/cm sec. degr. C.

Equation (1) can be derived as follows. Consider a length $\mathrm{d}x$ of the wire; at the ends of this element the temperature gradients are $\left(\frac{\mathrm{d}\tau}{\mathrm{d}x}\right)_1$ and $\left(\frac{\mathrm{d}\tau}{\mathrm{d}x}\right)_2$. By heat conduction therefore the following amount of energy is supplied to the element:

$$\lambda q\left[\left(\frac{\mathrm{d}\tau}{\mathrm{d}x}\right)_1-\left(\frac{\mathrm{d}\tau}{\mathrm{d}x}\right)_2\right]=\lambda q\,\frac{\mathrm{d}^2\tau}{\mathrm{d}x^2}\,\mathrm{d}x\,.$$

An amount of heat $\frac{Ai^2\varrho}{q}\,\mathrm{d}x$ is developed in the element by the current i. If the element is situated in a vacuum it loses energy to the surroundings only by radiation; the amount of this radiation is $u\,\sigma\,\tau\,\mathrm{d}x$, where it is assumed that the radiation is proportional to the temperature difference, which is permissible when the increases in temperature are small (see below for more detailed explanation). In the stationary state the energy supplied must equal the energy given off, and therefore

$$\lambda q\,\frac{\mathrm{d}^2\tau}{\mathrm{d}x^2}\,\mathrm{d}x+\frac{Ai^2\varrho}{q}\,\mathrm{d}x=u\,\sigma\,\tau\,\mathrm{d}x,$$

from which (1) follows.
In this derivation it is therefore assumed that ϱ, λ and σ are independent of the temperature; we shall see later what changes are necessary when this condition is no longer satisfied.

If the limiting condition is introduced that the increase of temperature at the terminals is zero ($x=\pm\,l/2$), then the equation has the following solution:

$$\tau=\frac{Ai^2\varrho}{\sigma u q}\left\{1-\frac{\cosh x\sqrt{\frac{\sigma u}{\lambda q}}}{\cosh\frac{l}{2}\sqrt{\frac{\sigma u}{\lambda q}}}\right\}\quad\cdot\;\cdot\;\cdot\;(2)$$

(cosh a is the hyperbolic cosine of a, *i.e.* the abreviated notation of $^1/_2\,(e^a+e^{-a})$; the expression hyperbolic tangent which occurs later stands for $\frac{e^a-e^{-a}}{e^a+e^{-a}}$). In fig. 3a this increase of temperature is drawn for different points of the filament.

At the middle the increase in temperature (t) is:

$$t=\frac{Ai^2\varrho}{\sigma u q}\left\{1-\frac{1}{\cosh\frac{l}{2}\sqrt{\frac{\sigma u}{\lambda q}}}\right\}=\frac{Ai^2\varrho}{\sigma u q}\left\{1-\frac{1}{\cosh K}\right\}(3)$$

where $K=\frac{l}{2}\sqrt{\frac{\sigma u}{\lambda q}}=l\sqrt{\frac{\sigma}{\lambda d}}$ for round wires

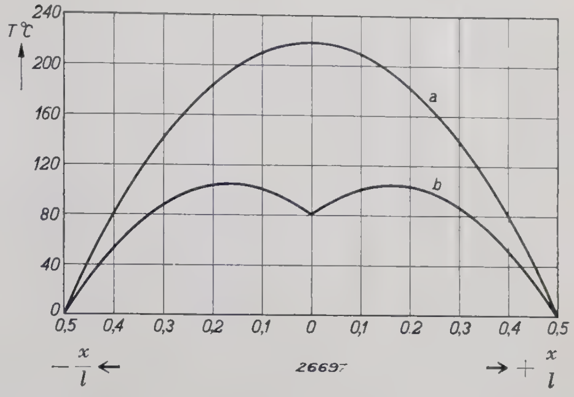


Fig. 3) *a*) Temperature of a stretched wire through which current is flowing.
b) Temperature of the same wire when a thermocouple is fastened at its middle point.

with the diameter d. The increase of temperature is therefore actually proportional to i^2. When K is small (this is usually the case in practical applications as we shall see later), we may write:

$$\cosh K=1+K^2/2,$$

and (3) becomes:

$$t=\frac{A\,i^2\,\varrho\,l^2}{8\,\lambda\,q^2}=\frac{A\,i^2}{8}\,\frac{\varrho\,l}{q}\,\frac{l}{\lambda\,q}=\frac{Ai^2}{8}\,R_g\,R_w\quad(3\mathrm{a})$$

In this expression R_g is the electrical and R_w the heat resistance of the filament. In (3a) the radiation constant δ no longer occurs due to the approximation. This fact will be found later to be very important.

We shall now pass on to the case where a thermocouple is fastened to the middle of the filament. This can be described in good approximation by calculating that a quantity of heat M is removed at the middle of the filament per second and per degree increase of temperature. The differential equation then becomes more complicated; we shall only give the result for the increase in temperature t_M at the middle of the wire:

$$t_M=\frac{Ai^2\varrho}{\sigma u q}\,\frac{1-\frac{1}{\cosh K}}{1+\frac{M\,\mathrm{tgh}\,K}{2\sqrt{\sigma\,\lambda\,u\,q}}}=\frac{t}{1+\frac{M\,\mathrm{tgh}\,K}{2\sqrt{\sigma\,\lambda\,u\,q}}}\quad\cdot\;\cdot\;(4).$$

The increase of temperature is therefore greater, the smaller M. The factor $\frac{\tanh K}{\sqrt{\sigma\,\lambda\,u\,q}}$ takes account of the fact that the heat lost flows to the middle of the filament from parts lying near the middle. For small values of K the following holds:

$$t_M = \frac{\dfrac{A\, i^2 \varrho\, l^2}{8\, \lambda\, q^2}}{1 + \dfrac{l}{4\, \lambda\, q} M} \quad . \; . \; . \; . \; . \quad (4a)$$

In this case also the increase in temperature is proportional to i^2. The influence of the heat conduction is less than in (3a). This is clear enough. In the first case a great increase in temperature could be attained by a high heat resistance of the filament; the supply of heat to the middle of the filament has now become an important factor. In *fig. 3b* we give an idea of the variation of temperature along the filament; the middle no longer has the highest temperature.

Finally the value of M must be expressed in terms of the dimensions and constants of the thermocouple. An analogous differential equation is valid here, but with different limiting conditions. The solution is the following:

$$M_1 = \frac{\sqrt{\sigma_1 \lambda_1 u_1 q_1}}{\operatorname{tgh} K_1}, \quad . \; . \; . \; . \; . \; . \quad (5)$$

where the subscript 1 indicates that the values are for one of the wires of the thermocouple. The same formula with the subscript 2 holds for the other wire; the length of the wires is $\frac{l_1}{2}$ and $\frac{l_2}{2}$; $K_1 = \frac{l_1}{2} \sqrt{\frac{\sigma_1 u_1}{\lambda_1 q_1}}$. The loss of heat through the whole thermocouple is:

$$M = M_1 + M_2.$$

At small values of K_1 (5) becomes:

$$M_1 = \frac{2\, \lambda_1 q_1}{l_1} \quad . \; . \; . \; . \; . \; . \; . \quad (5a)$$

If we introduce this value of M into (4) the equation becomes:

$$t_M = \frac{\dfrac{A\, i^2 \varrho\, l^2}{8\, \lambda\, q^2}}{1 + \dfrac{l}{2\, \lambda\, q} \left\{ \dfrac{\lambda_1 q_1}{l_1} + \dfrac{\lambda_2 q_2}{l_2} \right\}} \quad . \; . \quad (4b)$$

The temperature of the middle of the filament is therefore now expressed in the dimensions and constants of the wires of the thermo-couple.

Let us first consider the numerator of (4b). Leaving out the constants of the material we may write:

$$t_M \sim \frac{i^2 l^2}{q^2} \sim i^2 R_g^{\,2}.$$

The dimensions of the filament occur only in the form l/q; filaments, therefore, with different dimensions but with the same resistance undergo the same increase in temperature with a given current. The voltage drop caused by the filament, $i\, R_g = V$, is not dependent on the dimensions of the filament. If a definite rise in temperature must be attained with different currents, the resistance of the filament must be inversely proportional to the current. The energy necessary for a given temperature increase, V^2/R_g, is inversely proportional to the resistance, and therefore proportional to the current; thermo-ammeters for small currents, therefore, possess a greater energy sensitivity than those for heavy currents.

The foregoing remains true when the second term in the denominator is small with respect to one; this is the case when there is only a slight loss of heat through the thermo-couple, or when $l/2\, \lambda\, q$ is small. The latter is always the case with thermo-ammeters for larger currents ($i\, l/q$ must always be constant). If the second term may not be neglected, which is the case with thermo-ammeters for low currents, the sensitivity to energy is smaller. A small heat loss through the thermocouple is therefore favourable in such a case. Since λ_1 and λ_2 are usually given (the choice of material is determined by the thermo-electric properties), this can be achieved by making q_1/l_1 and q_2/l_2 small. The resistance of the thermo-couple $R_e = \frac{\varrho_1 l_1}{2\, q_1} + \frac{\varrho_2 l_2}{2\, q_2}$, however, becomes large as a consequence of this measure; a limit is thereby set to the reduction of M (see later). The dimensions of the thermocouple occur only in the form q/l, so that wires with the same electrical resistance cause the same heat loss.

In the above it is always assumed that the radiation may be neglected; this assumption is the basis of the approximation employed here.

With a given thermoelectric combination the above considerations are also valid for the thermal electromotive force E_{th}. The sensitivity of the thermo-electrometer is of course proportional to the thermoelectric force per degree. The current through the galvanometer i_m is the following, when R_m is the resistance of the meter:

$$i_m = \frac{E_{th}}{R_e + R_m},$$

where R_e is the internal resistance of the thermo-couple.

Connection of the measuring instrument to the thermocouple

We may continue with our considerations along two lines.

a) We may begin with a given thermocouple with resistance R_e, and ask what meter we must use in order to obtain the greatest deflection with a definite primary current i. To answer this we must calculate the voltage on the meter:

$$E_m = E_{th} \frac{R_m}{R_m + R_e}\,; \quad \frac{E_m}{E_{th}} = \frac{R_m/R_e}{R_m/R_e + 1} \,. \quad (6)$$

Fig. 4 gives a graphic representation of (6). The requirement is that the sensitivity to voltage of the meter (*i.e.* the deflection at a definite voltage on the meter) shall be so great that the meter has the desired deflection with the voltage calculated from (6). When $R_m = R_e$ the thermocouple gives off the greatest amount of energy to the meter. A meter with this resistance therefore may be the least sensitive to energy ($\frac{\text{deflection}}{\text{energy}}$ may be smallest); it is usually also the cheapest meter. A more sensitive meter may, however, also be used.

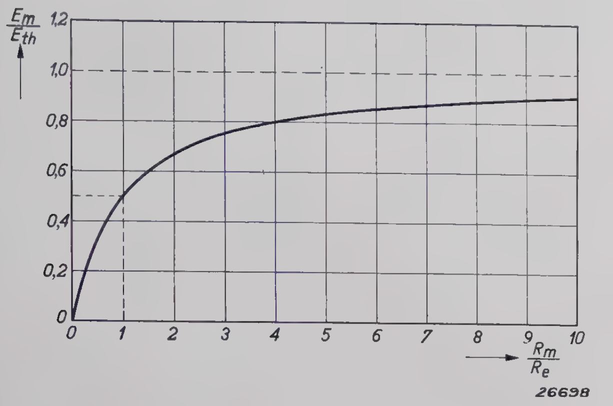


Fig. 4. Drop in terminal voltage of the thermocouple, when current is taken off by the meter. E_m/E_{th} is plotted as a function of R_m/R_e. When $R_m = R_e$ the most favourable energy transfer takes place.

b) We may begin with a given meter, and ask how the thermocouple must be constructed in order to give the greatest deflection on the meter. This problem is not so simple. It is clear that with a given thermal electromotive force, and therefore a given temperature of the junction, the voltage on the meter is highest when the resistance of the thermocouple is zero (see *fig. 5a* which is the same as fig. 4, but with a different abscissa). We have, however, seen that the loss of heat through the thermocouple becomes greater as the resistance is lowered, while the temperature increase of the junction is decreased by greater loss of heat through the thermocouple. The thermal electro-motive force is therefore diminished if the resistance of the thermocouple is reduced (see *fig. 5b*). The combination of these two effects is shown graphically in *fig. 5c*, where the voltage on the meter is plotted as a function of the resistance of the thermocouple at a constant current through the filament. If we pass from a high value of the resistance to a low value, the current through the meter at first rises because the total resistance falls, while the thermo-electromotive force changes very little; the current then falls again because the thermo-electromotive force falls and the total resistance no longer changes sufficiently. Fig. 5c is valid for a definite meter resistance; if the meter has a higher resistance, the maximum is shifted to the right, if the resistance is lower, it is shifted to the left.

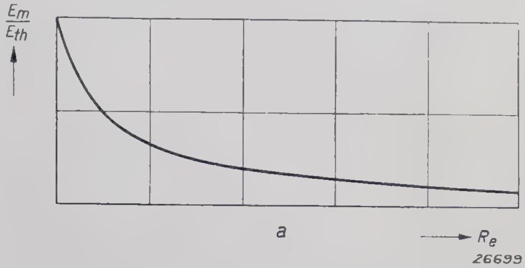


Fig. 5. *a*) Voltage on the meter as a function of the resistance of the thermocouple at a constant thermo-EMF.

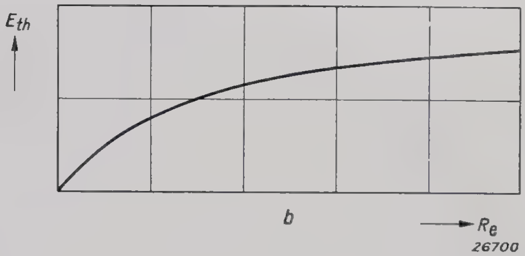


Fig. 5. *b*) Thermo-EMF as a function of the resistance of the thermocouple at a constant current through the filament.

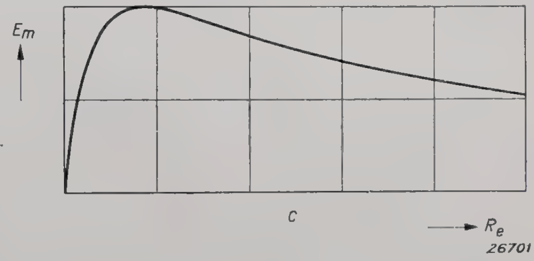


Fig. 5. *c*) Voltage on the meter as a function of the resistance of the thermocouple at a constant current through the filament.

Further discussion of the characteristic of the thermo-ammeter

In the deviation of the formulae it is assumed that ϱ, λ and δ do not depend upon the temperature. The derivation is therefore only valid for small increases in temperature. If these increases are not small, the dependence on temperature of these quantities must be taken into account. In that case, however, the differential equation is insoluble, so that the influence of this dependence must be estimated in some other way. This can be done very roughly by first giving the constants in the solution of the differential equation the values at room temperature, and then the values at the temperature of the middle of the filament; the difference between the two results indicates in any case the direction in which deviations may be expected. We shall discuss this for the various quantities which may be dependent on temperature.

With each individual quantity it will be found that the result of its dependence on temperature is that the characteristic is no longer truly quadratic. In favourable cases the deviations due to the different quantities may compensate each other.

ϱ. The temperature coefficient of the specific resistance has very different values for different materials; it is for example positive and about 0.4 per cent per degree centigrade for copper, platinum and iron, and practically zero for constantan and manganin. If ϱ is positive the resistance increases with increasing current through the wire, so that with a high current relatively too much energy is developed. The deflection of the galvanometer will thus be greater than proportional to the square of the primary current.

λ. The temperature coefficient of heat conductivity is much smaller than that of electrical resistance; it is weakly negative for the pure metals and positive for constantan and manganin. Experience has shown that its influence is slight; the reason for this lies in the above-mentioned fact that a small value of λ on the one hand improves the heat insulation of the filament, and on the other hand it prevents the conduction of heat to the thermocouple. A change in λ therefore will in the first approximation only influence the variation of temperature along the filament, but not the temperature of the middle. This does not of course hold for the loss of heat through the thermocouple, which is proportional to the heat conductivity of the thermocouple. If the latter has a positive temperature coefficient the result is that the deflection increases more slowly than proportional to the square of the current.

σ. The Stefan-Boltzmann law holds for the heat radiation of a black body. According to this law the amount of energy radiated per second and per square centimetre of the body is proportional to the fourth power of the absolute temperature. If the radiation takes place in surroundings at the temperature T_0, the radiation is then:

$$R = S\,(T^4 - T_0^4)\,\frac{\text{cal}}{\text{cm}^2\cdot\text{sec}\cdot\text{degree}^4}\,.$$

If the temperature differences under consideration are not great, this expression may be replaced by:

$$R = S\,a\,(T - T_0) = S\,a\,\tau.$$

The quantity a, however, now depends upon the temperature difference, and as a second approximation we may write:

$$a_\tau = a_0\,(1 + \alpha\,\tau).$$

The constant α is approximately independent on the temperature difference, and between 20° C and 100° C it is equal to $+$ 0.6 per cent per degree Centigrade. The dependence of δ on temperature results in the fact that the increase in temperature is less than the formula indicates, and therefore the deflection of the galvanometer changes less than proportional to the square of the primary current.

In addition ϱ, λ and σ, the thermo-e.m.f. per degree, the resistance of the thermocouple and the heat resistance from the middle of the filament to the junction of the thermocouple may also depend upon the temperature. In many cases the temperature coefficient of the thermo-e.m.f. may be neglected. The resistance of the thermocouple forms merely a part of the resistance of the meter circuit, so that its influence may be slight. It is very difficult to make an estimation of the heat resistance of the connection between filament and thermocouple, and of the way in which this depends upon the temperature; its influence becomes less according as the heat resistance of the thermocouple is increased. With poorly made junctions, however, this influence may very well be felt, so that the connection must be very carefully made.

From the above discussion it follows that particularly the radiation can cause great deviations from the quadratic variation of the characteristic. It is therefore desirable to make the radiation as slight as possible. We have seen in the discussion of the expression for the temperature at the middle of the filament that this temperature is independent of the dimensions for a given resistance of the filament. The radiation, however, is proportional to the surface of the wire; to make the radiation small therefore the dimensions must be kept small.

At small values of K the radiation constant σ no longer occurs in the formulae. The value of K is therefore a measure of the influence of radiation. K is proportional to $l/\sqrt{d}$; the energy sensitivity on the other hand is proportional to l/d^2.

With constant energy sensitivity ($l/d^2 = C_1$), therefore, $C_1\,d^{3/2}$ must be made as small as possible; d must therefore be small.

The same holds for the dimensions of the thermocouple. Wires with different dimensions but with the same electrical resistance cause the same loss of heat; if the dimensions, and therefore the surface, are small, the radiation has the least influence. Therefore short thin wires must be used to construct thermojunctions with a quadratic characteristic. By this means the heat capacity of the thermo-couple is decreased at the same time, so that the final deflection of the meter is more quickly attained. A limit is set to the reduction of the dimensions, however, because such reduction diminishes the ability to withstand overloads.

Overloading and sensitivity

We have seen that the highest temperature of the filament does not occur in the middle of the wire, but somewhere between the middle and the terminals. If the current through the filament is made too high, the filament will burn through at those spots. It is therefore important that the ratio of this maximum temperature to the temperature at the middle should not be too great. A measure for this ratio, which is not easy to calculate, is the ratio of the average temperature of the wire to the temperature at the middle. For small values of K it is:

$$\frac{\bar{\tau}}{t_M} = \frac{2/3 - 4/15\,K^2 + \dfrac{2\,M}{\sqrt{\sigma\lambda u q}}\,(1/6\,K - 13/180\,K^3)}{1 - 5/12\,K^2}$$

At a given value of K (thus at a given value of $l/\sqrt{d}$) the ratio becomes greater if d is decreased; the dependence of d, however, is less, the smaller the value of K. Further it is clear that a thin wire is more quickly damaged than a thick one at a given temperature; this is a reason for not using too thin a wire.

With large current thermo-junctions K is so small that the maximum temperature is practically equal to the temperature at the middle. In this case the permissible current is not limited by the melting of the wire, but by the overheating of the cement with which the thermocouple is fastened to the filament. It is very difficult to find a cement which is attacked only at a higher temperature than that which injures the filament.

The overloading of thermo-junctions for weak currents is therefore determined by the velocity of evaporation or the melting point of the filament, that of those for heavy currents by the properties of the cement.

In direct relation to overloading is the indication of the current for which the thermo-junction is intended. Since the degree of attack on the filament upon overloading depends on the length of time during which a given current is sent through the wire, it is impossible to indicate a maximum permissible current, if the time is not also indicated. A suitable measure is for example the current at which the filament remains absolutely undamaged for one minute. At the same time it is desirable to know the current at which the instrument can be used continuously. In practice it is then desirable to use a still lower current in order to have a margin of safety.

In the case of the Philips thermo-junctions the current is indicated at which the thermo-electric force is 12 mV; in addition the maximum current is given at which the instrument may be used continuously and the current at which it is quickly burnt through. We may call a thermo-junction which gives 12 mV at 10 mA, a 10 mA instrument.

It is therefore only possible to speak of a thermo-junction for a definite maximum current; the current at which the full deflection of the meter is obtained depends upon both thermocouple and meter.

The following must also be kept in mind. Suppose that we have a certain meter and the corresponding thermocouples for 10 mA and 20 mA. The resistance of the filaments of these couples are respectively 75 and 23 ohms. In a given circuit the resistance of the 10 mA couple may be too high, for instance when the couple must form part of a tuned circuit. In this case the resistance of the 20 mA couple is perhaps permissible. That couple may then be used if a more sensitive meter is available which gives the full deflection at 10 mA, when used with the 20 mA couple. In certain cases therefore a dial instrument will not be used but a very sensitive mirror galvanometer, in order to be able to use a thermocouple with low resistance for low currents also.

Reversal effect

The first thermo-junctions constructed exhibited a strong reversal effect, *i.e.* the deflection changed when the direction of the current of the primary direct current was changed. There may be two causes for this phenomenon:

a) One of these may be the Peltier effect, which is the reverse of the thermo-electric effect. When current is sent through a thermocouple the junction becomes colder if, upon heating it, a current would

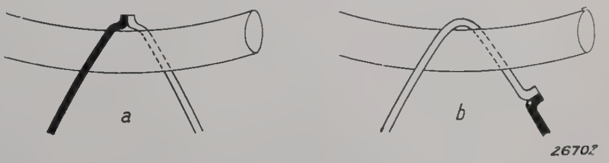


Fig. 6. *a*) Peltier effect in thermocouples. The junction of the couple lies on the filament and therefore part of the heating current passes through it.
b) Reversal effect in thermocouples. The junction of the couple lies near the filament, but the heating current passes through a short section of one of the wires of the thermo-couple.

have occurred in the same direction, and vice versa. The Peltier effect therefore occurs in the original thermo-electric ammeter by Klemenčič, and also in the case of the commonly used bridge circuits which we shall not discuss here. With modern thermocouples also the effect may appear when the thermo-junction is not electrically insulated from the filament, and when it lies exactly on the filament (see *fig. 6a*). In this type of construction part of the primary current also passes through the junction of the thermocouple and gives rise to the Peltier effect. This may be avoided by placing the junction near but not on the filament.

b) Even when the junction does not lie on the filament a reversing effect may also appear (see *fig. 6b*). At the point where filament and thermocouple touch each other, part of the primary current will always pass through part of the thermocouple. Due to the resistance of the latter a potential difference will arise which leads to a small extra current through the meter whose direction is reversed when the direction of the primary current is reversed. In order to avoid this the thermocouple must be insulated from the filament; when this has been done the reversal effect will be found to have disappeared and the thermocouple can be calibrated with direct current.

Speed of indication

The final deflection is not rapidly reached with a thermo-ammeter. The main reason for this is that a temperature equilibrium must be established in the filament and the thermocouple. Since the thermocouple itself does not carry the primary current, the heating up of the junction must take place from the filament by conduction, for which some time is necessary. A type of construction is possible in which the thermocouple also serves as filament (see *fig. 7*); in this case the heat is developed in every element of volume of the thermocouple, so that only a small amount of heat needs to be transported by conduction, and the final deflection is quickly attained. An elaboration of this construction is formed by the bridge arrangements in which a number of thermocouples are joined to form a square; the disadvantage of this method is the presence of a strong Peltier effect.

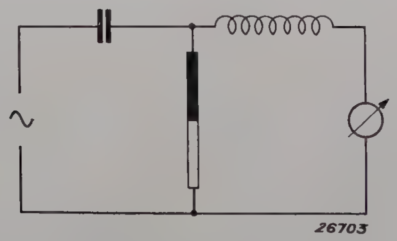


Fig. 7. Thermocouple with direct heating. The condenser is introduced so that the direct voltage given by the couple may not be short-circuited by the source of alternating current. The self-inductance is introduced to prevent the alternating current from passing through the direct current metre.

As was noted above, the heat capacity also has some influence on the speed of indication; therefore small dimensions are desirable. The resistance of the thermocouple may also effect the speed of indication because with too low resistance the damping of the metre is considerable.

Dependence of the indication on frequency

The heat development in a wire is independent of the frequency of the alternating current used for heating up to very high frequencies. At very high frequencies, however, the so-called skin effect appears, and the resistance, and therefore the heat development also, are greater than at low frequencies. For the thickness of wire used the influence of this effect is only appreciable at wave lengths of less than one metre, so that it need not usually be taken into account.

It is quite another question with the influences of various capacities (see *fig. 8*). The capacity in parallel with the filament is the cause of part of the current to be measured not passing through the filament, and the result is that the deflection of the metre is too small. This is sometimes compensated by the self-induction of the filament. The capacity between the supply leads has the same effect. There is further capacity between the filament and the thermocouple which is connected with earth capacitatively through the galvanometer. This capacity is further increased by the fact that the leads of the filament and those of the thermocouple are close together in the pinch

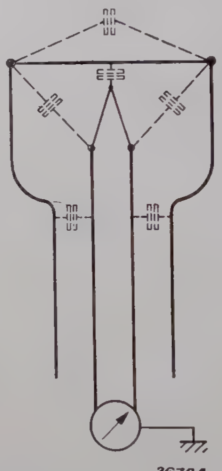


Fig. 8. Diagram of a thermocouple with the various parasitic capacities.

of the bulb and in the base. This capacity may be partially reduced by using thermocouples without bases in measurements at very high frequencies. The third kind of capacitive influence, the capacity of the leads to earth, is hereby also very much reduced. In order to overcome the last-mentioned influence it is absolutely essential that one side of the filament be earthed.

The influence of these parasitic capacities becomes greater the higher the resistance of the filament. A thermocouple with a filament having a resistance of 20 ohms gives reliable indications at a wave length of 6 metres within 1 per cent; when the thermocouple is used without a base the indication is still reliable within 1 per cent at wave lengths of 3 meters.

Advantages in the use of thermo-ammeters

In conclusion we give the following list of the advantages connected with the use of thermocouples for measuring alternating current.

a) The effective value of the alternating current is measured because use is made of the development of heat, and therefore of a mechanism which varies essentially with the square of the current. For this reason the measurement is very little affected by the presence of higher harmonics in the current measured, and it is not at all affected by the phase of these harmonics. This is a common property of all thermal instruments.

b) Up to a very high frequency the indication is independent of the frequency of the current measured.

c) The energy consumption is small compared with that of dynamometers and soft-iron instruments.

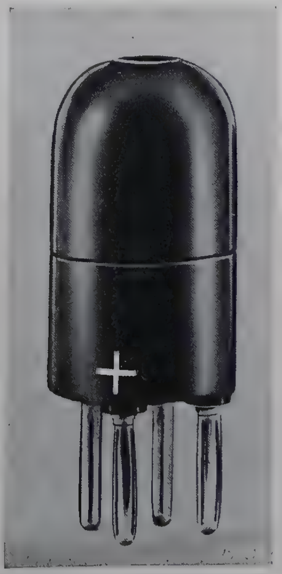


Fig. 9. Thermocouple assembled.

d) The delicate part of the measuring arrangement, the thermocouple itself, is easily renewable; in this connection the quadratic, or at least reliably constant, characteristic is also important.

Survey of the Philips thermojunctions

The Philips thermo-electric meters are constructed with the above considerations in view. *Fig. 9* is a photograph of a fully assembled thermocouple and *fig. 10* shows the interior of such an instrument. The cover serves not only for decoration, but also for shielding the instrument from heat radiation from the surroundings.

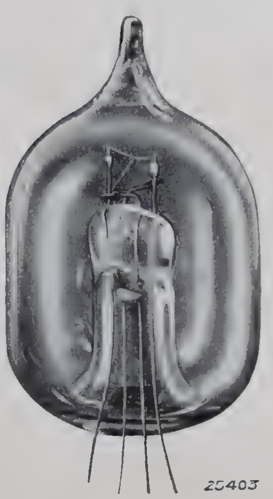
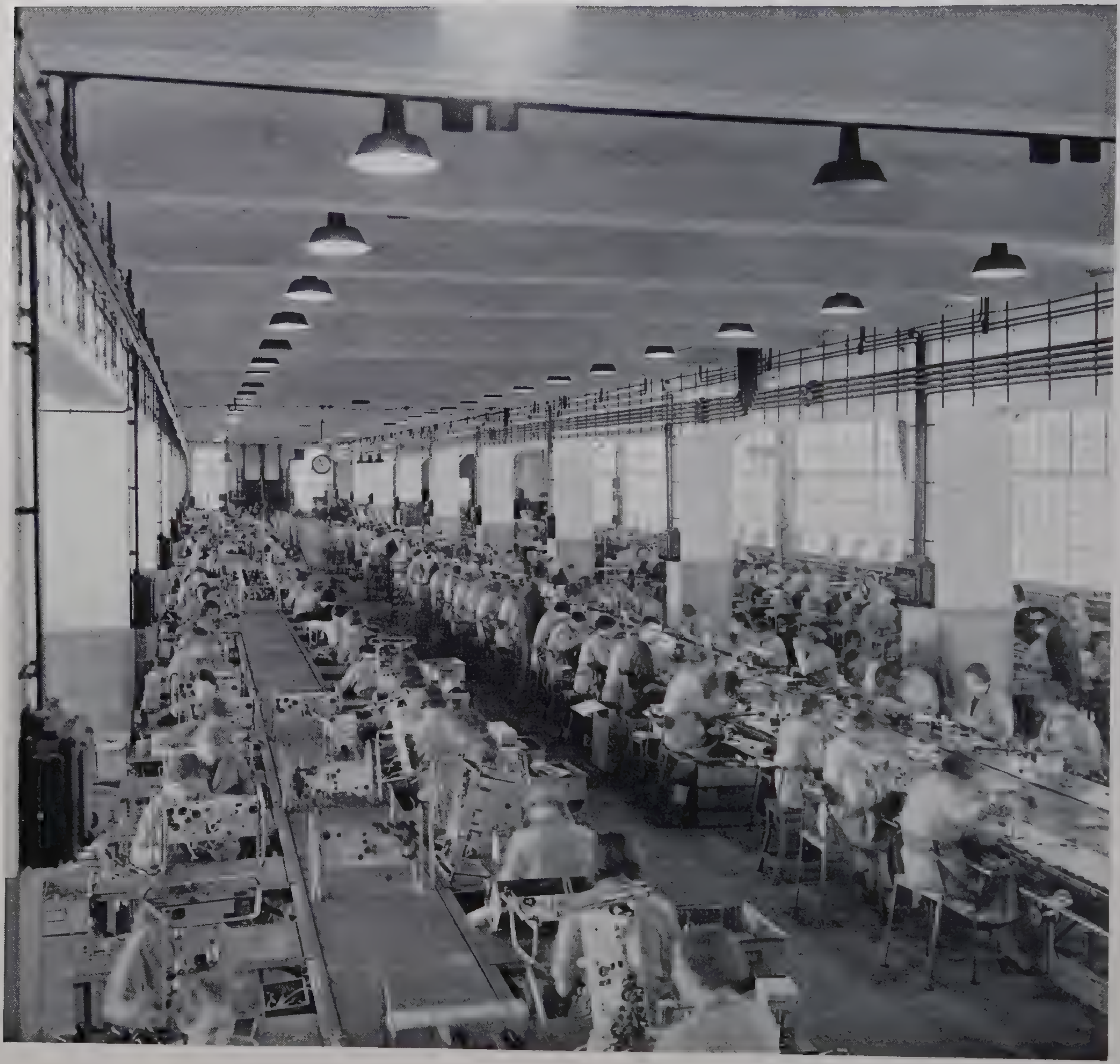


Fig. 10. Interior of a thermocouple.

The *table* gives a survey of the various properties of the instruments. With all types the temperature coefficient of the resistance of the filament is small; for most measurements it may be neglected. The indication is practically quadratic up to half the filament current, where the thermo-electric force is 12 mV; the deviation from the quadratic variation is 2 per cent at the most in this range, the thermo-electromotive force is about 4 mV at that current, so that a full deflection can still be obtained with sensitive dial instruments. The thermocouple is insulated electrically from the filament; the instruments can therefore be calibrated with direct current.

Type number	12 mV EMF at approx. mA	resistance of the filament ohm	resistance of the thermocouple	continuous use up to mA	maximum permissible current mA
Th1	10	75	5	15	20
Th2	20	23	3	30	40
Th3	40	7.5	3	75	100
Th4	100	2.2	3	150	200
Th5	200	1.1	3	300	350

ASSEMBLY OF WIRELESS RECEIVERS



The photograph shows two conveyor belts at which radio receivers are being assembled. The belts convey parts from one worker to the next. The girl takes the arriving piece of work from the belt, performs the necessary operations which consist in the mounting of parts, taken from the stock at her side, into the chassis by welding, soldering or screwing. For a smoothly running process the girl should just have finished her task when the next piece of work arrives. In this way the chassis is gradually assembled and at the end of the belt it can be mounted in its cabinet.

THE ILLUMINATION OF THE NEW LEAGUE OF NATIONS PALACE IN GENEVA

by L. C. KALFF.

628.972

The League of Nations Palace is intended for the housing of all League organisations (except the Bureau de Travail which is already definitely established elsewhere), which up to now have been accommodated in various buildings in Geneva. The different parts of this organization are naturally very diverse in character. There are administrative departments which are in daily use, assembly halls which are scenes of activity now and again for several days or weeks when there are congresses and meetings of international committees, and a considerable portion of the building is intended for the very momentous and festive gatherings on important occasions, for which banquet halls and monumental rooms are necessary. The extensive group of buildings includes four sections, as may be seen from the ground plan (*fig. 1*), namely the offices of the secretarial department, the section for the League Council, in the main axis the hall of the representatives of the Assembly with committee rooms surrounding it, and finally the library.

The illumination of the secretarial department is mainly ultilitarian, and its design is for the most part determined by the dimensions of the mains. The latter are not very heavy so that in the offices, which are in light colours, diffuse direct lighting had chiefly to be used, with one diffuser (type DM; *fig. 2a*) with a lamp of 150 decalumens (111 W) per desk, so that an illumination of about 65 lux is obtained on the desk, and at the same time a sufficient general illumination (*fig. 3*). Only in several low-ceilinged rooms in which the typists sit, and where one would be too much restricted in the placing of the desks if direct lighting were used, are indirect reflectors (type WX; *fig. 2b*) used, with a uniform illumination of about 110 lux. In this way the placing of the desks is left quite free (*fig. 4*). In the evening this wing of the building with its many lighted windows makes a very fine effect from the „Cour du Sécrétariat", as may be seen from the vignette at the head of this article.

In the section for the League Council the rooms are lighted in the same way with the exception of several rooms for which special plans were made in collaboration with the architects. In the first place there is the "Salle du Conseil" which offered particularly difficult problems. The entire hall is

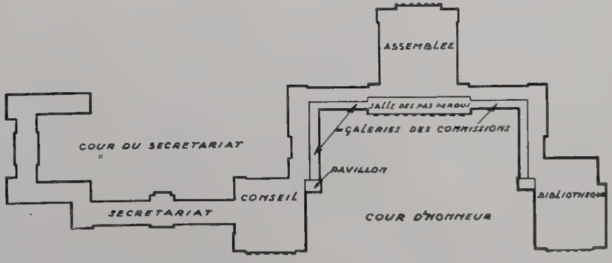


Fig. 1. Plan of the League of Nations Palace.

executed in polished grey marble and so called "Camaieu painting" in grisaille on a gold background. The result is poorly reflecting, dark walls and ceiling, with locally strongly reflecting surfaces.

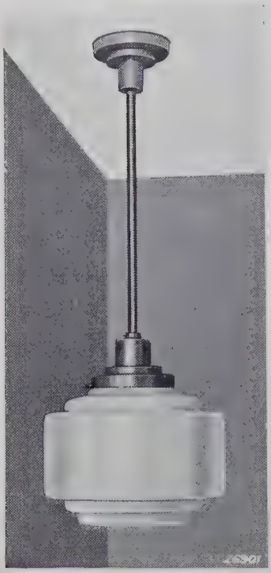


Fig. 2. *a* DM Diffuser

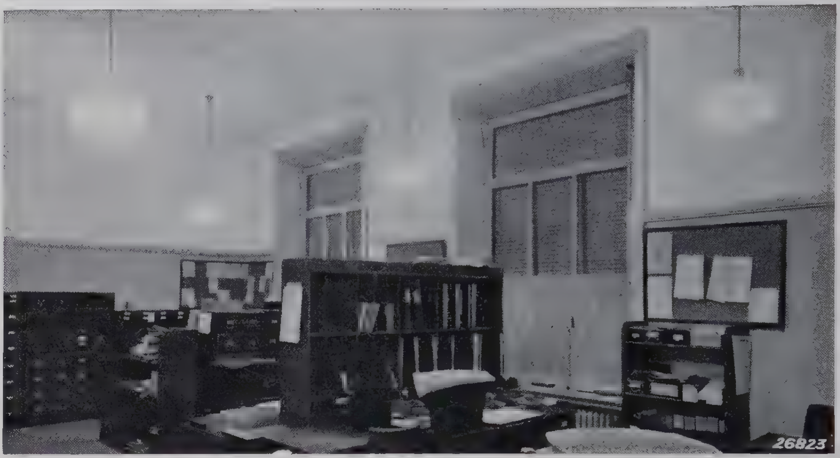


Fig. 3. Illumination with diffusing fixtures DM of one of the rooms of the secretarial department of the League of Nations.

The only possible illumination was the installation of extensive ornamental lighting fixtures with large diffusely radiating surfaces with as low brightness as possible. For this purpose Perzel of Paris constructed large bronze bowls 2 metres in diameter with thick glass rings behind which the lamps were placed in white reflectors (*fig. 5*). The light-coloured curtains before the five enormous windows are illuminated decoratively from above with silver reflectors, but not too intensely, since otherwise the Council, with its back to the windows, would be in a poor light as seen from the hall, namely only in silhouette.

The committee rooms all open on the approximately 160 metre long gallery which is 10 metres high. The gallery ends in square chambers which are lighted indirectly by four large bronze standards by Perzel, with lamps of 500 watts which light the ceiling (*fig. 6*), and are provided with a frosted glass rim to avoid sharp-edged shadows on the walls. An

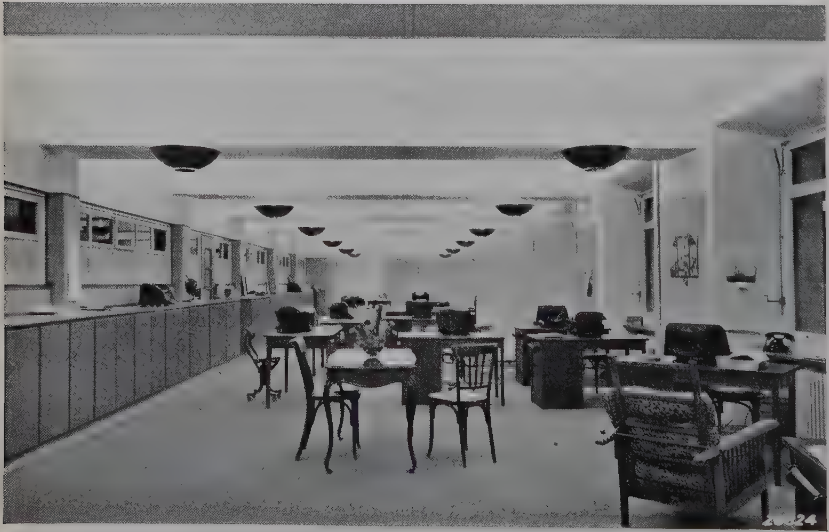


Fig. 4. Indirect illumination with WX fixtures; the placing of the desks is here independent of the lighting.

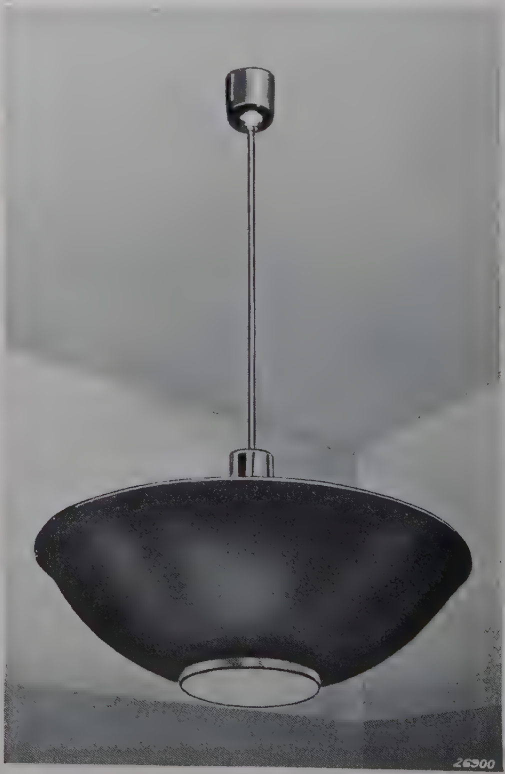


Fig. 2. *b* WX Indirect lighting fixture.

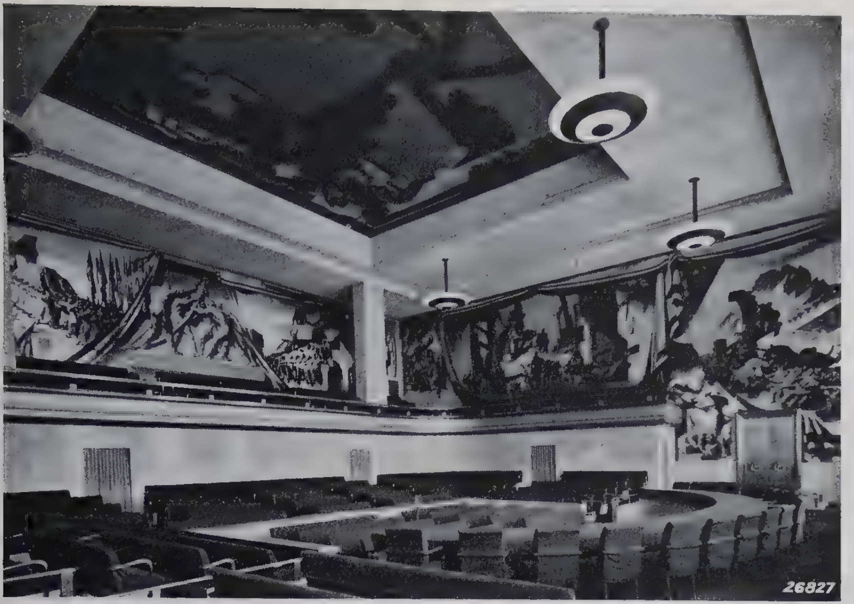


Fig. 5. View of the "Salle du Conseil".

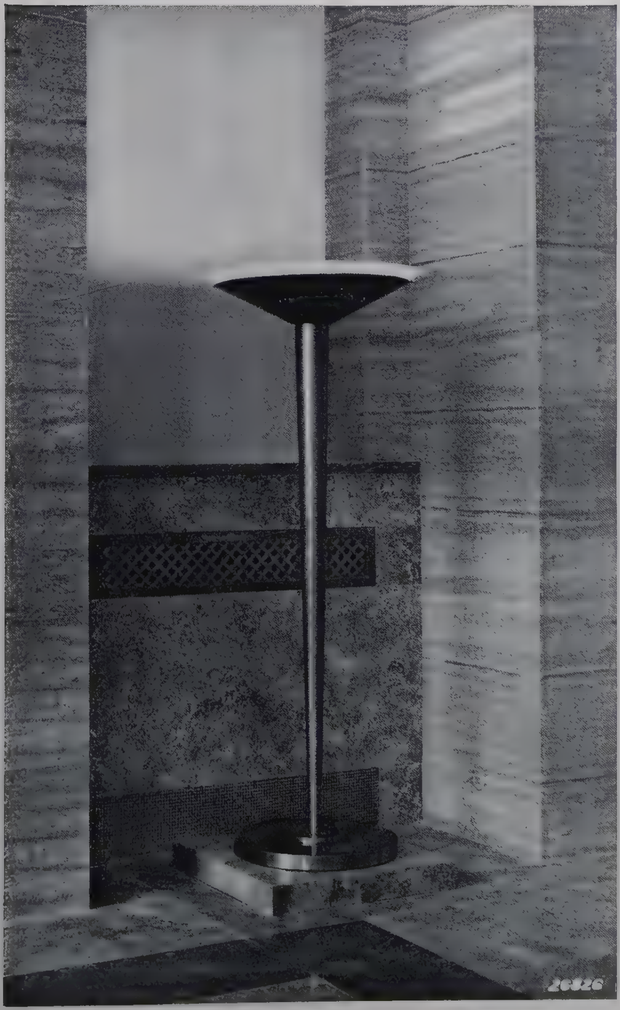


Fig. 6. Large bronze standard by Perzel for indirect lighting with 500 watt lamps.

indirect illumination with small 40 watt lamps at distance of 20 cm in a continuous chromium plated reflector forms the main illumination of the gallery. Most of the committee rooms are lighted indirectly from vaulted portions of their ceilings (*fig.* 7). Three small silvered parabolic reflectors per linear metre are introduced in recesses on rails previously fixed. Each reflector contains a lamp of 40 watts and a very pleasant uniform illumination is obtained. In front of every reflector a convex, partially frosted glass had to be introduced to avoid light spots, while at the same time the light reflected from the recesses themselves further promotes this uniformity. Since many of the recesses had already been finished before the lighting was projected, the correct proportioning of the lighting system was very difficult. In some cases, instead of the silvered reflectors, a continuous chromium plated reflector had to be mounted with five lamps per metre to get a uniform illumination.

The "Salle des Pas Perdus" (*fig. 8*) which is treated in a particularly decorative manner, opens off the middle of the great gallery, and serves as a foyer to the great "Salle de l'Assemblée". The dark polished granite floor and the marble columns (*fig. 9*) here again presented great dificulties. The main illumination was finally designed as indirect lighting from a built-in recess in the gallery which runs along the 56 metre long hall (see cross section *E* in fig. 8). Five reflectors (type SC 170; *fig. 10*) per linear metre with 60 watt lamps were installed in this recess and light the ceiling (16.8 kW). To limit direct vision of the lamps from the gallery white metal partitions were introduced between the reflectors, while the whole was made dust proof with bent glass plates which are slightly frosted on the inside to eliminate light streaks. The short sides of the long hall have no reflectors as the portions of the ceiling at the ends would otherwise be more intensely lighted than the rest, but for the sake of uniformity of the whole only bare 40 watt lamps with five per linear metre are mounted there behind the bent glass plates. The other long side of the hall has nine enormous bronze window frames 12 metres high, each frame enclosed by a bronze moulding. In this moulding (detail D in fig. 8) there is a continuous row of tubular lamps "Philinea", 80 watts per metre) with white enamelled reflectors which light the white surface of moulded plaster between the marble columns. This gives a very dignified but also festive character to the hall. For this illumination 9 times 42 "Philinea" lamps 50 cm long were necessary altogether (15.12 kW). Between the windows are eight bronze standards (fig. 6) by Perzel with 500 watt lamps which give light accents (cf fig. 9). In total 16 + 4 + 15 = 35 kW is installed.

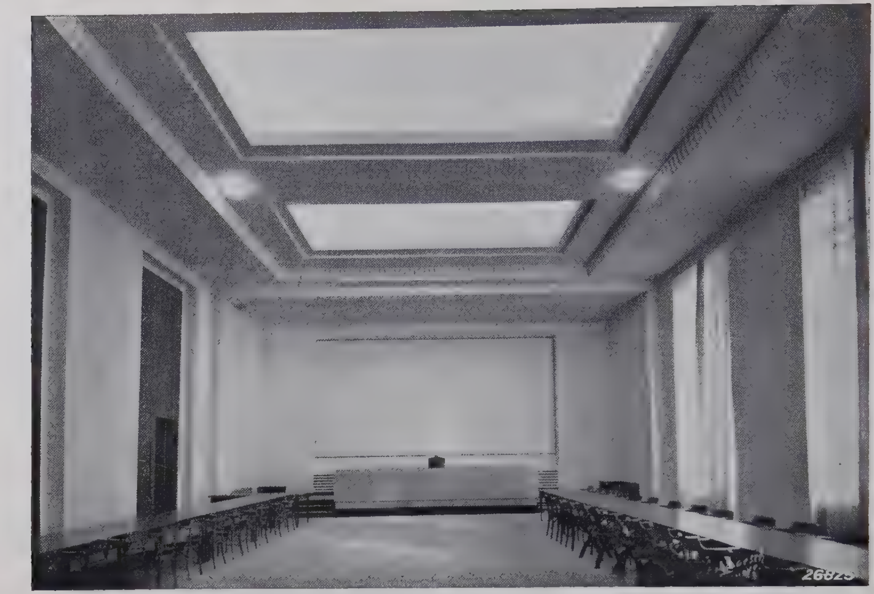


Fig. 7. Indirect lighting of one of the committee rooms.

The great "Salle de l'Assemblée" (*fig. 11*) presented a particularly complicated problem because in this huge hall the illumination had to be entirely part of the architecture (*fig. 12*), and not only on the podium and the speakers chair, but also on the floor, was a very good illumination necessary, while also in the two deep galleries the public and the press had to be able to read and write. The main illumination was obtained in imitation of the daylight illumination by 132 silvered reflectors with lamps of 300 and 500 watts above the glass middle section of the ceiling. This section of the ceiling consists of so-called thermolux glass, two layers of clear glass with a layer of glass wool between, and is very fine in appearance and gives good diffusion.

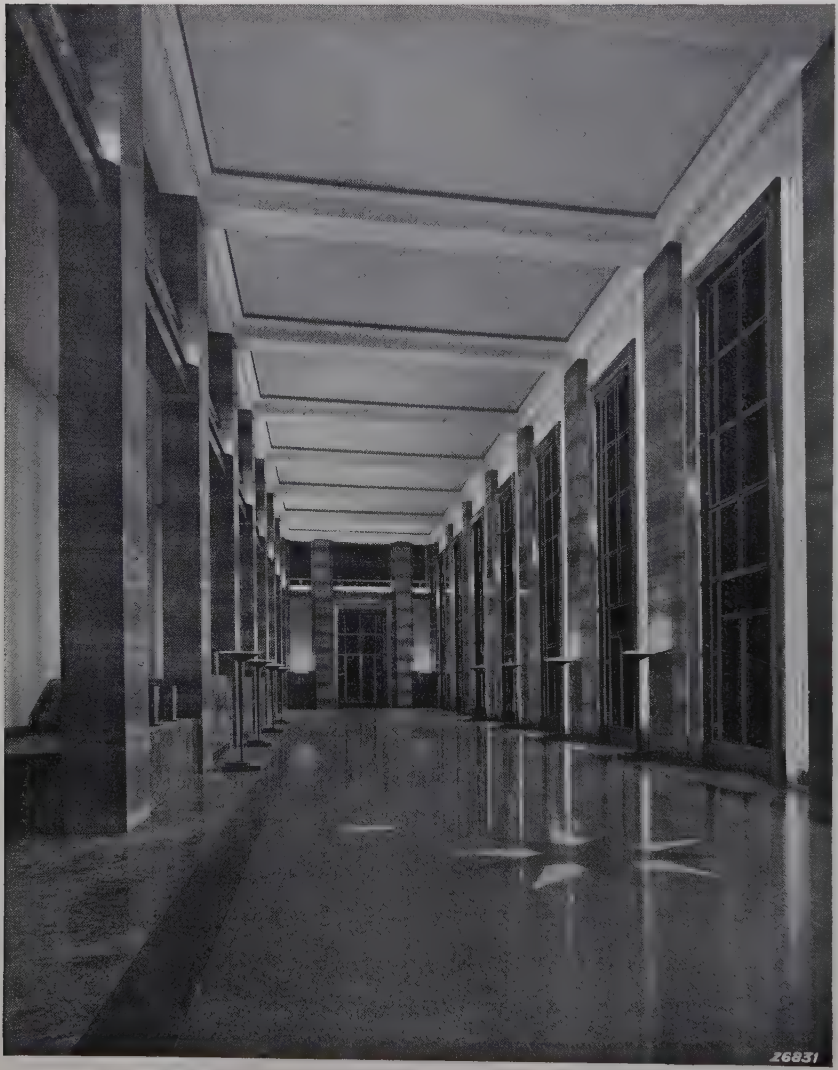


Fig. 9. View of the "Salle des Pas Perdus".

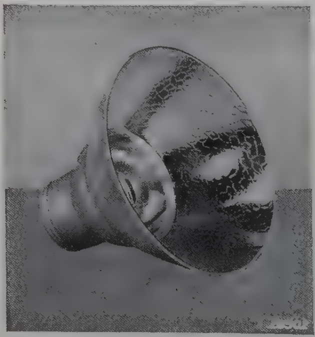


Fig. 10. Reflectors, types SC 170 and SC 130.

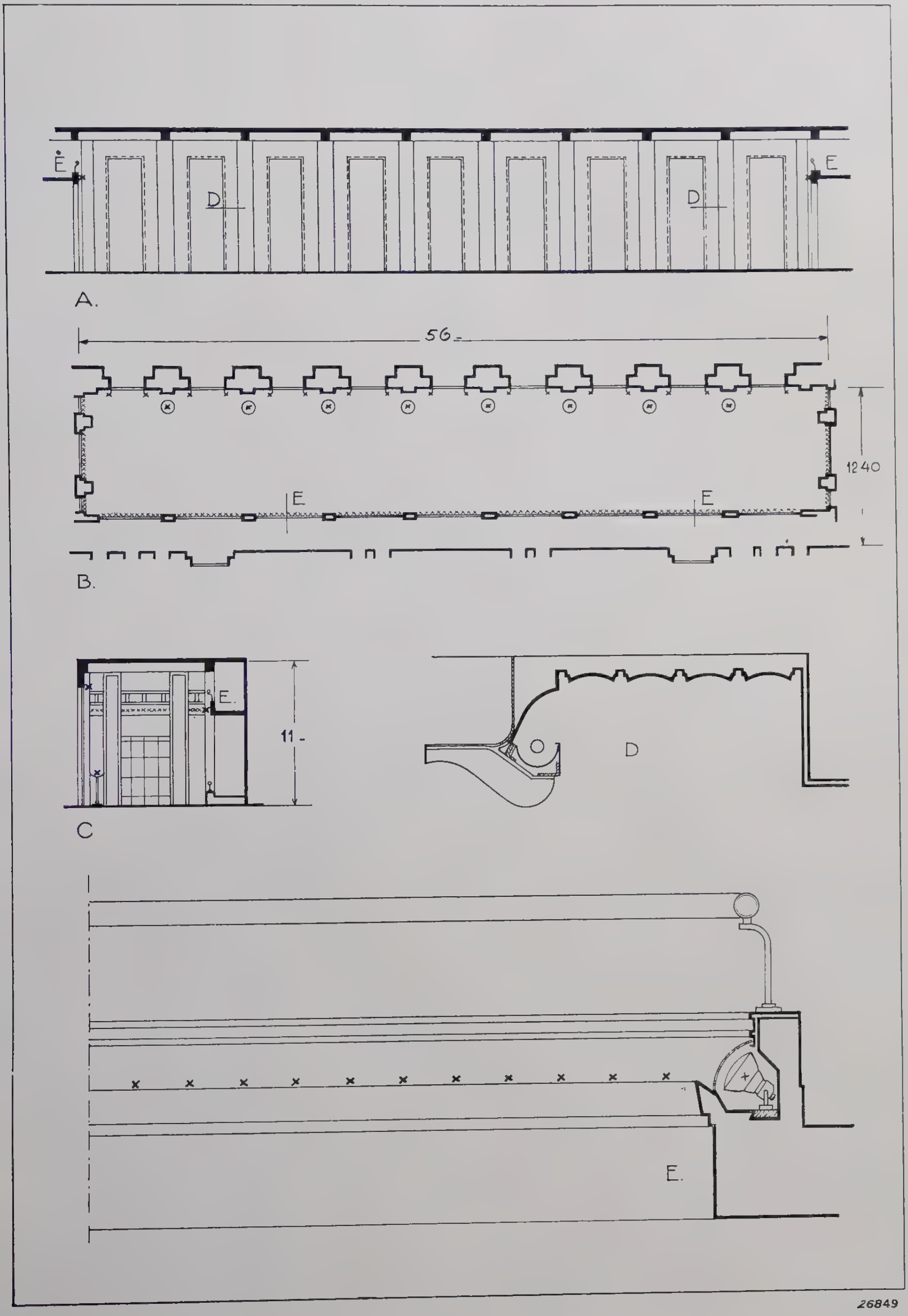


Fig. 8. Construction scheme of the "Salle des Pas Perdus".

A longitudinal cross section of the hall,
B ground plan of the hall,
C cross section through the width of the hall,
D horizontal cross section of the light recesses around the windows,
E detail of the indirect ceiling illumination in the gallery, in vertical cross section.

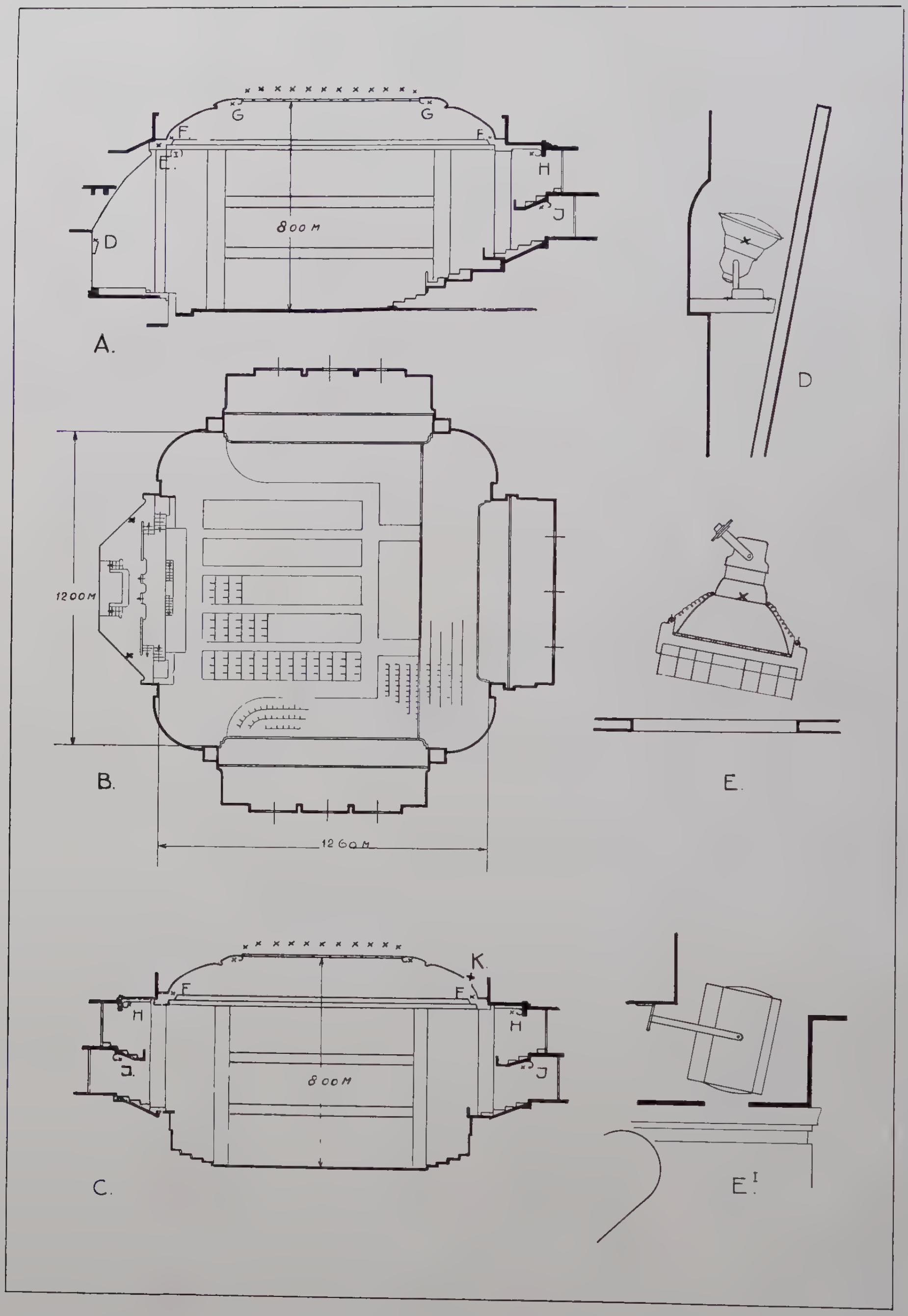


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Fig. 11. Construction scheme of the "Salle de l'Assemblée".
A longitudinal section of the hall,
B ground plan of the hall,
C crosswise section of the hall,
D detail of the rear wall of the podium in vertical cross section,
E and E^I, normal and film lighting installations in the light recess above the podium; in fig. 12 the latter is visible as four light spots directly under the loudspeakers.

A flat white band runs around this glass surface and is lighted by 25 watt lamps in a bronze recess (at *G* in fig. 11). Outside of this there is a wide curved border of plaster which has been sprayed with a soft sound-absorbing material. This border is uniformilly lighted by a row of silvered reflectors with 150 watt lamps hidden in a plaster recess which is gilded on the outside (at *F* in fig. 11). These lamps can be reached for repair above the hall on travelling bridges above the glass and behind shutters for the recesses. These shutters are necessary primarily for the ventilation system. The ordinary illumination of the podium is by five silvered reflectors type SC 255 with 200 watt lamps which are hidden in the gilded recess above the podium. To prevent direct vision into the reflectors from the hall they are provided with louvres (detail *E* in fig. 11). In addition to this ordinary illumination of the podium there is also an installation for film lighting (detail E^{I} in fig. 11), which may be seen as four spot lights in fig. 12 directly under the loud speakers. The marble wall behind the podium has a small light recess with 25 watt lamps in reflectors type SC130 (at *D* in fig. 11), for the purpose of placing a light accent on the chief detail of the hall. The galleries have indirect illumination from long strips of white plaster in the ceiling which are lighted with 25 watt lamps in chromium-plated metal reflectors (at *H* and *I* in fig. 11).

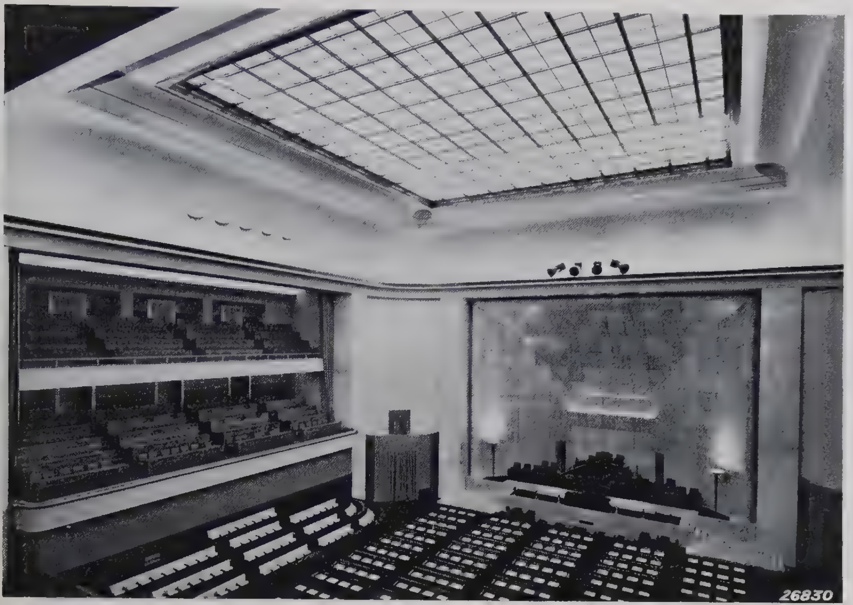

Fig. 12. Vieuw of the „Salle de l'Assemblée".

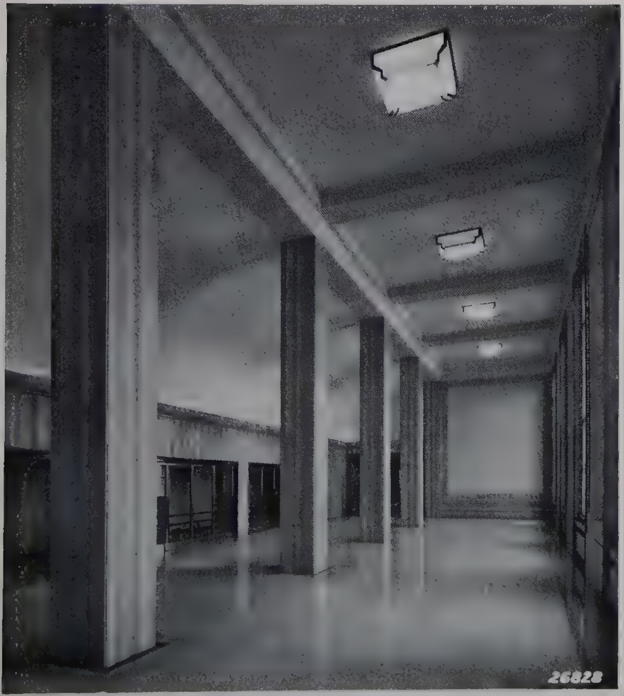

Fig. 13. Lighting of the side galleries of the "Salle de l'Assemblée".

In the preceding paragraph we mentioned the installation for film lighting. To facilitate news reel reporting during meetings and discussions it was necessary to be able to illuminate intensely but for brief periods the podium with the speaker, and also certain sections of the hall where the delegations from the different member countries sit, very intensely for short times. In order to do this in a way which is the least disturbing for the speakers it must be possible to raise the level of illumination at the place to be photographed to 1500 lux or higher for several minutes whenever desired. For this purpose four permanent spot lights with mirrors and condenser lenses are installed above the podium, each of which has a power of 3 kW. These lamps light the chairman's table, and the speakers position. Since the light comes from very high up, it is not disturbing, however, side lighting from the hall must also be provided since otherwise the lighting of the subjects to be photographed would be very poor.

In addition there are five round openings in the ceiling on the right side of the podium which can be closed (see fig. 12, in the lighted part of the ceiling at the left). Behind these openings are five large mirror reflectors, two permanently directed on the podium and provided with 5 000 watt lamps, and three with 10 000 watts which can be directed on 25 different sections of the floor of the hall. The operator of these lamps is in telephonic communication with the film cabins which are situated under the first gallery.

The side galleries of this hall have one part which is lighted indirectly from a marble alcove by 25 watt lamps in reflectors of type SC 130 (*fig. 13*). These lamps provide a uniform illumination of the sloping portion of the ceiling formed by the underside of the first gallery. The rest of the space is lighted by four large square ceiling ornaments by Perzel of Paris. Behind the white diffusing glass of each ornament there are 18 lamps of 65 watts.

It would lead us too far afield if we were to describe in detail the lighting of every hall and room in the building. We shall therefore conclude with a description of the temporary flood-light installation of the front of the building giving on the "Cour d'Honneur" which was used at the opening (*fig. 14*). The requirement in this case was that on evenings of festive occasions the outside of the building should be well lighted, and in fact so well lighted that it might be seen from the other side of Lake Geneva, which is fairly broad at this point. At the same time, however, it was required that persons in the building should be able to reach the gardens by way of the grand staircase without being blinded. It was of course difficult to find a single solution for both problems. Fig. 14 shows fairly well the result achieved.

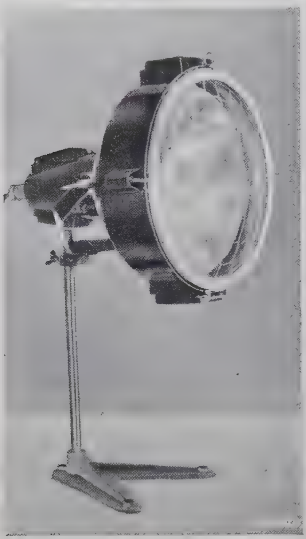

Fig. 15. *a* FLC Fixture.

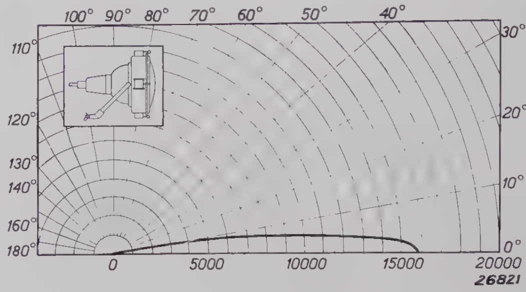

Fig. 15. *b* Light distribution curve of a FLC mirror reflector.

For this purpose three different batteries of 24 mirror reflectors, type FLC (*fig. 15*), with searchlight lamps of 1000 watts were set up on the roof of the wing leading to the secretarial department. The intention is to make a permanent installation some time in the future, which will give not only a good illumination for a distant view of the building, but which will also illuminate the "Cour d'Honneur" for those present in it.

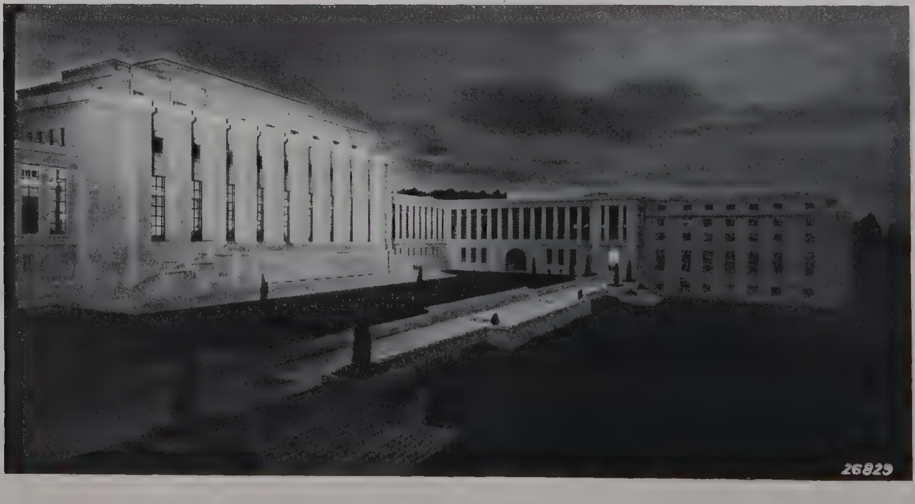

Fig. 14. Lighted exterior giving on the "Cour d'Honneur".

A SIMPLE ARRANGEMENT FOR THE MEASUREMENT OF THE SPECIFIC RESISTANCE OF LIQUIDS

by A. CLAASSEN.

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A measuring arrangement is discussed which consists of the simple "Philoscope"[1]), universal measuring bridge, an alternating current generator for 1000 cycles per second and a measuring vessel. This set-up is intended especially for carrying out the control measurements on the conductivity of liquids which are regularly made in many industries.

Measurement of the resistance of liquids

In many industries the specific conductivity, *i.e.* the reciprocal of the specific resistance, of liquids must be regularly checked. This may be so in the case of the waste water, the boiler water and the rinsing water in laundries where the progress of the washing process must be determined. In the sugar technique also it is simpler, instead of the elaborate determination of the ash of the sugar, to measure the specific resistance of the sugar solution which is directly connected with the desired weight of ash.

In this article an arrangement is described for the measurement of the specific resistance in which use is made of the simple electrical measuring bridge previously described in this periodical[1]). The problem of the measurement of specific resistance comes down to the measurement of the resistance of a liquid in a measuring vessel which has been calibrated with certain standard liquids. In the measurement of the specific resistance of liquids in practice the difficulty arises that it is not easy to determine the correct length and cross section of the column of liquid to be examined. If for example two equally large electrodes at different potentials are placed at a given distance apart in a liquid, the lines of force will not run absolutely mutually parallel from one electrode to the other, but a certain bending of the lines of force will occur, so that the effective cross section of the column of liquid will be greater than the area of the electrodes themselves, unless the cross section is restricted in space by a non-conductor. If, however, the specific resistances of several liquids have been determined by means of a vessel in which the bending of the lines of force has been made impossible in some way, these liquids can be used for the calibration of a more simply constructed vessel, which at the same time may be better adapted to the requirements of practical measurements. With this calibrated vessel the specific resistances of other liquids can then easily be measured.

The measurement of the resistance of a liquid is a problem which presents various difficulties. It is impossible to measure this resistance with direct current as may be done with a metal conductor, since when a direct current is sent through a liquid situated between two electrodes immersed in the liquid certain changes take place at the electrode (for instance the development of gas or precipitation), which are accompanied by the appearance of definite potential differences between metal and liquid and acting against the current. The voltage applied between the electrodes, therefore, is not the same as the true potential difference between the ends of the column of liquid, and it is impossible to deduce the resistance of the column of liquid from the voltage applied and the curernt measured. The potential differences occurring in such a case are called polarization voltages and the phenomenon itself is called polarization.

The influence of polarization is obviated by measuring the resistance with an alternating current of sufficiently high frequency. Also if the measuring vessel is suitably constructed the influence of polarization can be practically neglected, since the polarization voltages have no opportunity of building up in the short time during which the current flows in a given direction. We shall first study the influence of polarization in the alternating current circuit.

The decomposition products which are formed at the electrodes due to the current, result in the appearance of an opposing electromotive force V_p which we shall assume to be proportional to the amount of electricity which has passed through, q:

$$V_p = -Pq = -P\int i\,\mathrm{d}t\,, \quad \cdot \cdot \cdot \quad (1)$$

which is entirely permissible at not too low frequencies. This formula reminds us of the formula for the voltage V on a condenser C with a charge q:

$$V = -\frac{q}{C} = -\frac{1}{C}\int i\,\mathrm{d}t\,. \quad \cdot \cdot \cdot \quad (2)$$

The polarization voltage V_p corresponds exactly in its behaviour with the voltage which occurs between two condenser plates due to a charge q, when the capacity is:

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[1]) Cf.: Philips techn. Rev. **2**, 270, 1937.

$$C = \frac{1}{P} \quad \cdots\cdots\cdots \quad (3)$$

If R is the resistance of the column of liquid, the ohmic loss of voltage is iR and the voltage on the liquid is equal to the sum of iR and V_p. The measuring vessel therefore behaves like a resistance R and a capacity equal to the reciprocal of the polarization factor P connected in series (*fig. 1*),

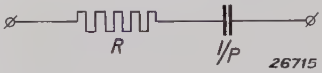

Fig. 1. Substitution diagram for the measuring vessel as part of an alternating current circuit.

so that its impedance for sinusoidal alternating current with an angular frequency ω is:

$$Z = \sqrt{R^2 + \frac{P^2}{\omega^2}} \quad \cdots\cdots \quad (4)$$

The influence of polarization is, according to formula (4), small when:

1) the frequency is sufficiently high,
2) the polarization factor is kept small, which can be done by giving the electrodes a large surface, since P is inversely proportional to the area of that surface,
3) the resistance of the liquid is high.

Care must be taken that the alternating voltage be as free of harmonics as possible. According to formula (4), the impedance of the measuring vessel will no longer be the same for the different harmonics as soon as the polarization is appreciable. This means that it is then impossible to bring the measuring bridge into equilibrium for a non-sinusoidal alternating current, since the different harmonics would require different adjustments.

The measuring arrangement

The arrangement which has been developed for the measurement of the resistance of liquids consists of:

1) the "Philoscope" universal measuring bridge type GM 4140 (*fig. 2*), which has previously been described [1]),
2) a generator for 1000 cycles: GM 4260 (*fig. 3*),
3) the measuring vessel GM 4221 (*fig. 4*).

In order to use the measuring bridge with a separate 1000 cycles generator the normal bridge voltage should be disconnected from the input terminals. The generator GM 4260 offers the possibility of choosing between a frequency equal to the mains frequency and a constant frequency of 1 000 cycles independent of the mains frequency for supplying the bridge part of the measuring bridge. The second frequency is especially intended for the measurement of resistance of liquids, since it is sufficiently high to allow one to neglect polarization with the type of measuring cell used, and on the other hand it prevents disturbance from unfavourable capacitative influences. The oscillator valve in the generator is provided with a variable gridleak, so that it is possible by adjusting for weak oscillation to ensure that the alternating voltage is purely sinusoidal at all loads.

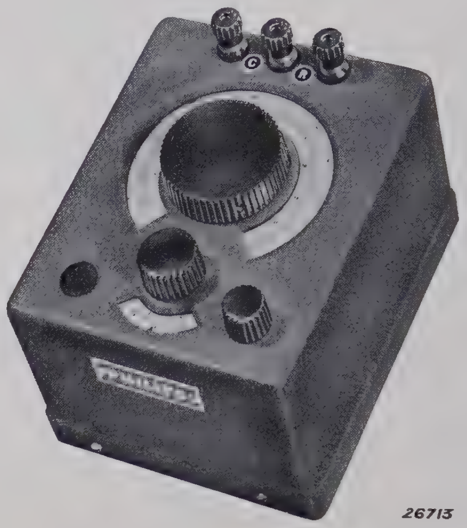

Fig. 2. "Philoscope" universal measuring bridge, type GM 4140.

The measuring vessel (see fig. 4) is constructed as an immersion cell. The platinum electrodes, each with a surface of about 1 cm², are placed

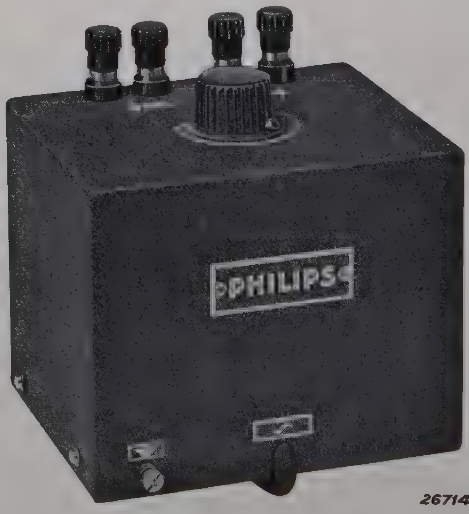

Fig. 3. GM 4260 Generator for the excitation of alternating current with a frequency of 1000 cycles per sec.

vertically at a distance of about 8 mm from each other and joined to the copper leads by means of platinum wires fused into the glass. The copper leads in turn make contact with the terminals. The outer surfaces of the electrodes are entirely covered with glass which has been applied in the molten state, and are held rigidly in place by a glass support. The electrodes are completely protected by the robust outer glass jacket of the measuring cell. This outer jacket has openings at the bottom and at the side to make it easier to fill it with the liquid.

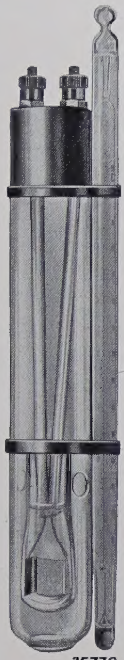

Fig. 4. Measuring vessel GM 4221 for the measurement of the specific resistance of liquids.

The following advantages are obtained by this method of placing the electrodes:

1) no air adheres to the electrodes upon immersion, as may be the case with horizontal electrodes and which might produce large errors in the determination of the resistance;
2) the lines of force in the liquid are quite fixed, since they are bounded by the outer glass wall, while the liquid automatically reaches a sufficient height above the upper edge of the electrodes upon immersion.

The specific resistance ϱ of a liquid is proportional to the resistance R of the measuring vessel filled with the liquid, and we may write:

$$\varrho = cR \quad \cdots\cdots\cdots \quad (5)$$

in which c is a constant characteristic of the measuring vessel (cell constant).

This cell constant is determined by calibrating the vessel with a solution of known specific resistance. The value of the cell constant is engraved on its neck. (For cells of the above construction it is about 2 in most cases).

An expedient which is very important for the practical avoidance of polarization is the platinizing of the electrodes. The electrodes are covered with a thin layer of platinum black (or platinum sponge) by electrolysis, so that their effective surface is many times enlarged. The platinizing of the electrodes has one objection, namely that the very finely divided platinum sponge adsorbs dissolved substances from the solution very strongly (especially acids and bases, to a lesser degree salts), and does not immediately give them up in more dilute solutions. Platinizing is especially recommended for the measurement of solutions with a low specific resistance. If one is concerned only with solutions which do not have a very low specific resistance, greater than 1 000 ohm cm for instance, it is better to carry out the measurements with bare metal electrodes, which can be obtained by dissolving the platinum black in *aqua regia*; the danger of polarization in such cases need not be feared.

With electrodes platinized in the correct way it is possible to carry out accurate measurements in the range extending from solutions with a specific resistance of about 20 ohm cm to solutions with the highest specific resistance occurring (several hundred thousand ohms cm). With solutions having a specific resistance less than 20 ohm cm polarization still occurs to a slight extent; this polarization could only be avoided by using very much larger platinum electrodes and thereby making the cell very expensive, or by making the distance between the electrodes very great, so that in the first place the cell becomes awkward in shape, and in the second place the measurements of higher specific resistances can no longer be carried out accurately. It is, however, possible to take into account the influence of polarization, which is manifested in a decrease of the cell constant (10 - 15%), by calibrating the cell with solutions of very low specific resistance, as for example sulphuric acid of maximum conductivity (sp. resist. 1.3 ohm cm) or a saturated solution of sodium choride (sp. resist. 5 ohm cm). If the absolute value of the conductivity in this range is of less importance, relative measurements of great accuracy are always possible.

In the measurement of the conductivity of poorly conducting solutions it is necessary to take account of the conductivity of the water used. If the conductivity of the water is χ_{H_2O} and the measured conductivity of the solution $\chi_{sol.}$, then the amount contributed by the dissolved substances to the conductivity of the solution is:

$$\chi_w = \chi_{sol.} - \chi_{H_2O} \cdot$$

Good distilled water has a specific resistance of about 200 000 ohm cm. With water distilled very carefully in the absence of carbon dioxide specific resistances of 10^6 ohm cm can be attained.

The influence of the temperature on the specific resistance of liquids is very great. In practically all aqueous salt solutions it becomes 2.0 - 2.5 per cent lower for every degree Centigrade increase of temperature. With most acids this value is 0.9 - 1.6 per cent, with alkali solutions 1.9 - 2.0 per cent. For accurate measurements an accurate measurement of the temperature within 0.2° C is necessary.

THE EXAMINATION OF THE MACROSTRUCTURE OF MATERIALS AND PRODUCTS WITH THE HELP OF X-RAYS. V

by J. E. DE GRAAF. 539.26

When a manufactured article, the product of various processes, is found in the end to possess flaws, these flaws may have arisen in the material and may be independent of the form of the article. Such flaws are most likely to appear oftenest when the material has attained its final form or position by way of the state. Examples of such cavities and enclosures have been given in this series in the discussion of the examination of cast and welded articles [1]). On the other hand the faults may have arisen during the process of giving the material a particular shape. The more trivial faults, such as for example due to the fact that the correct measurements have not been kept to in the process of turning, seldom offer material for an X-ray examination, because such faults are usually discovered in the inspection preceding delivery.

A structural process which, however, certainly calls for X-ray examination is rivetting which has also been treated in this series [2]). It was pointed out that defects in the crystal structure which may arise during these processes do not fall within the reach of absorption investigation.

Faults in assembly

In certain cases faults may arise without change in the material and independently of its form. These may be faults in the assembly, *i.e.* in the combination of perfect parts to a whole by soldering, cementing, fastening with bolts, connecting with wires, etc. In this case X-ray examination is again useful in order to sift out the faulty pieces at intermediate stages, and to trace the causes of faults in returned pieces. In addition X-ray investigation alone may make a certain process possible as a manufacturing method.

An example of the latter case is offered in the use of X-ray photography in the Philips industry in the manufacture of X-ray tubes and of certain transmitter valves. The construction of both of

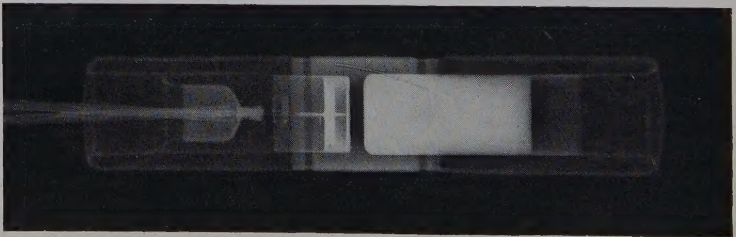

Fig. 1. Reduced X-ray photograph of an X-ray tube; the relative position and separation of the electrodes in the chrome-iron cylinder can only be seen in the X-ray photograph.

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[1]) Philips techn. Rev. 2, 377, 1937; 3, 93, 1938.
[2]) Philips techn. Rev. 2, 350, 1937.

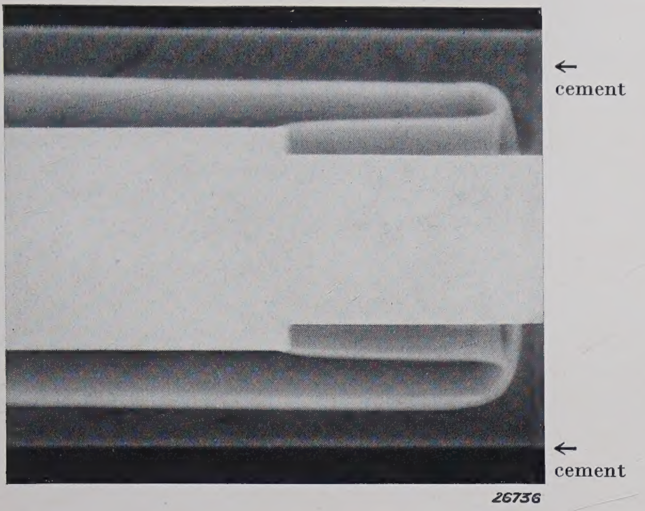

Fig. 2. Terminal assembled with bad cement for the connection of a high tension cable with an X-ray tube (gas bubbles and cracks in the cement).

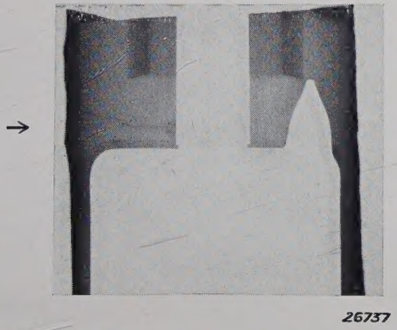

Fig. 3. Breakdown in a terminal for the connection of a high tension cable with an X-ray tube. The cause (a gas bubble in the cement) and the track of the breakdown may be clearly seen (at →).

these is distinguished by the use of an optically opaque chrome-iron cylinder in which the vital parts of the tube are housed. These parts are then fused with glass to the cylinder in a joint which is proof against high vacuum. *Fig. 1* gives the reduced X-ray photograph of an X-ray tube. On the basis of this photograph it is possible to discover whether the electrodes are at the proper distance from each other. The same procedure is followed in the manufacture of transmitter valves, where in addition the X-ray photograph is used to discover any possible change in the position of the electrodes which might have come about during the shock test [3]).

Another important sphere of application in assembly check tests is that of high voltage insulators and cables. No air spaces may occur between the parts of such insulators or cables, because with the high field strengths used, the air spaces by their ionization, would initiate breakdown. The components are therefore fastened together with a cement in which, however, gas bubbles are sometimes formed. *Fig. 2* shows the gas bubbles and even cracks in a terminal fastened with a quite inefficient cement. The terminal was intended for the connection between a high voltage cable and an X-ray tube. *Fig. 3* shows how the electrical breakdown of such a terminal appears in a photograph. The cause of the breakdown may here be seen (an air bubble in the cement), whereas if the cement had been melted out it would have disappeared entirely. With high tension insulators of artificial resin the X-ray photograph [4]) makes it possible to check the position of the pressed-in metal parts.

A third sphere of application lies in the examination of electrical apparatus. It may be a question of a simple cord in which a strand of wire is broken or of a complicated piece of apparatus which consists of many parts. In the filter shown in *fig. 4*, for example, a short circuit occurred which disappeared every time the wax was melted out, but reappeared again when it was poured in. By means of an X-ray photograph taken with the wax in place, the short circuit could be traced. Broken or

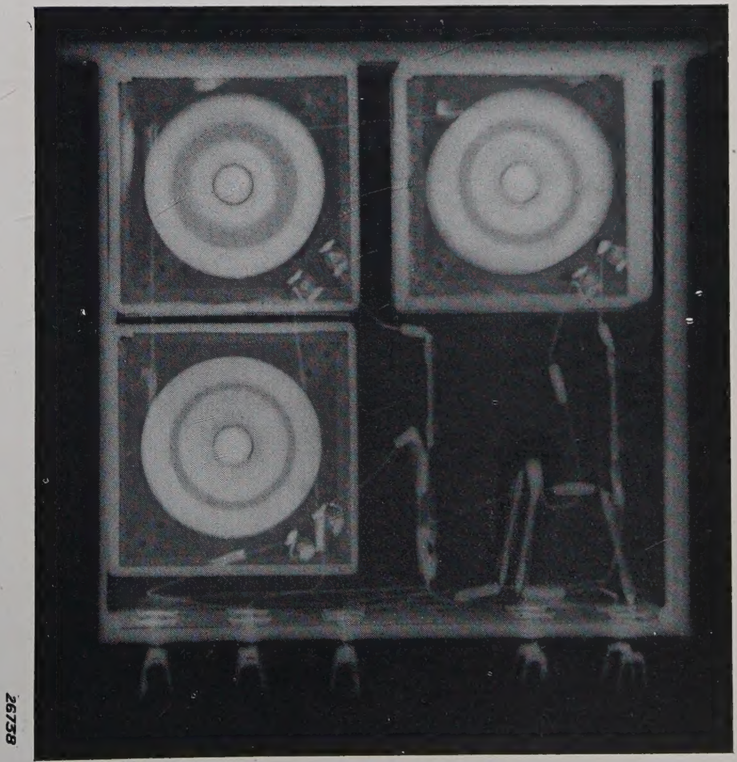

Fig. 4. Electrical filter. Short circuits, faulty soldering and air bubbles in the mass (lower right) can be observed in such a photograph.

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[3]) Philips techn. Rev. **2**, 115, 1937.

[4]) Philips techn. Rev. **1**, 257, 1936.

badly soldered contacts also, as far as they are not obvious from the functioning of the apparatus, can often be found most simply in an X-ray photograph. How the correct placing of coils in a can may have suffered by the process of impregnation is shown in *fig. 5:* the primary coil of a transformer has sunk down out of the secondary coil so that the transformer no longer functions properly.

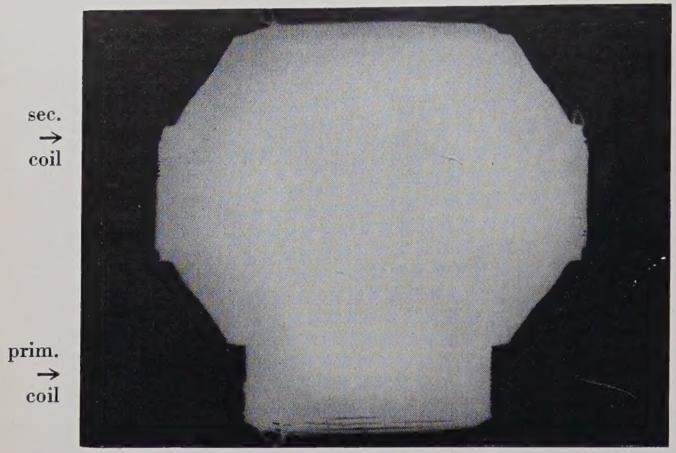

Fig. 5. The primary coil of a transformer impregnated when in its housing , has sunk down out of the secondary coil, as this X-ray photograph of the two coils in their relative position plainly shows. The iron core has been removed.

Finally assembly inspection with the help of X-rays is also applied to mechanical problems. In this case naturally it is the finer pieces of apparatus rather than large machines in which X-ray inspection is valuable. *Fig. 6* gives an example in the form of a carburetter in which a detail, such as the position of the petrol supply tubes, may be seen very clearly. The presence and position of stop pins, the tightness of nuts and the presence of self-locking nut washers are other examples of the application of X-ray examination in this branch of engineering.

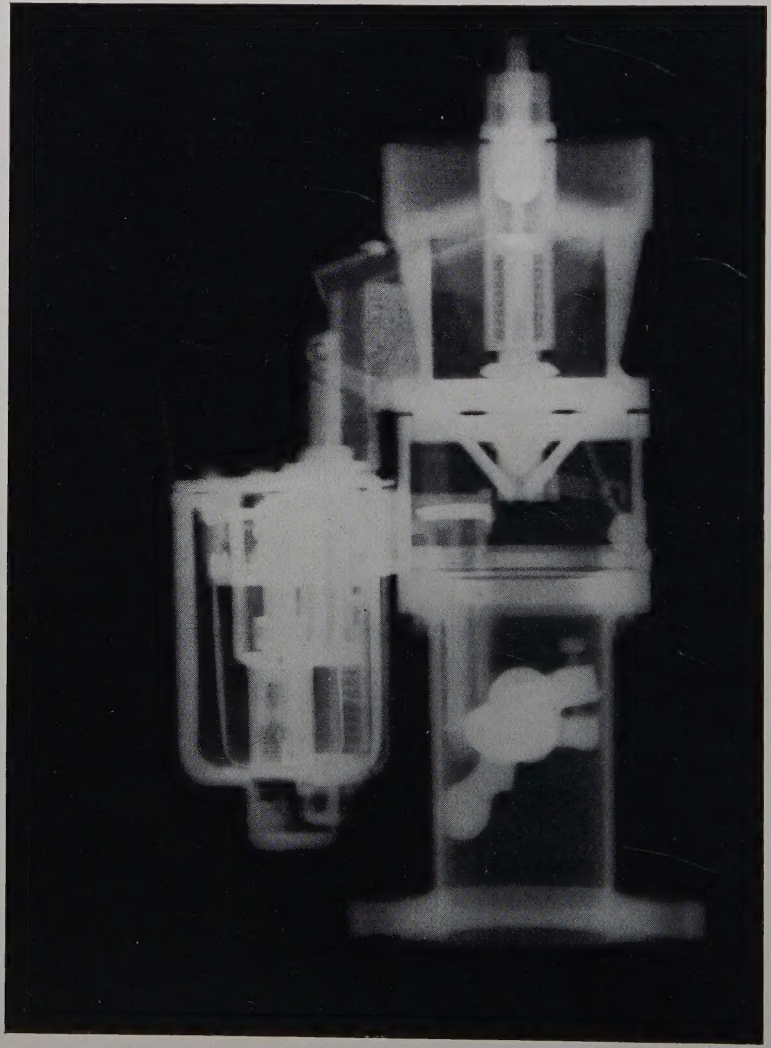

Fig. 6. X-ray photograph of a carburetter in which many details of the complicated structure may be plainly observed.